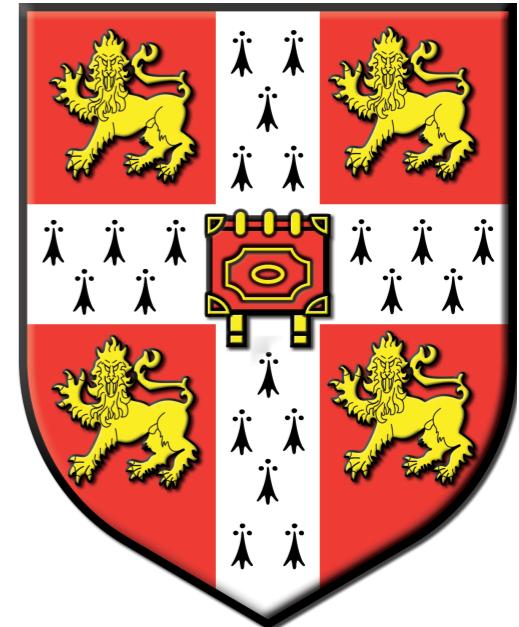




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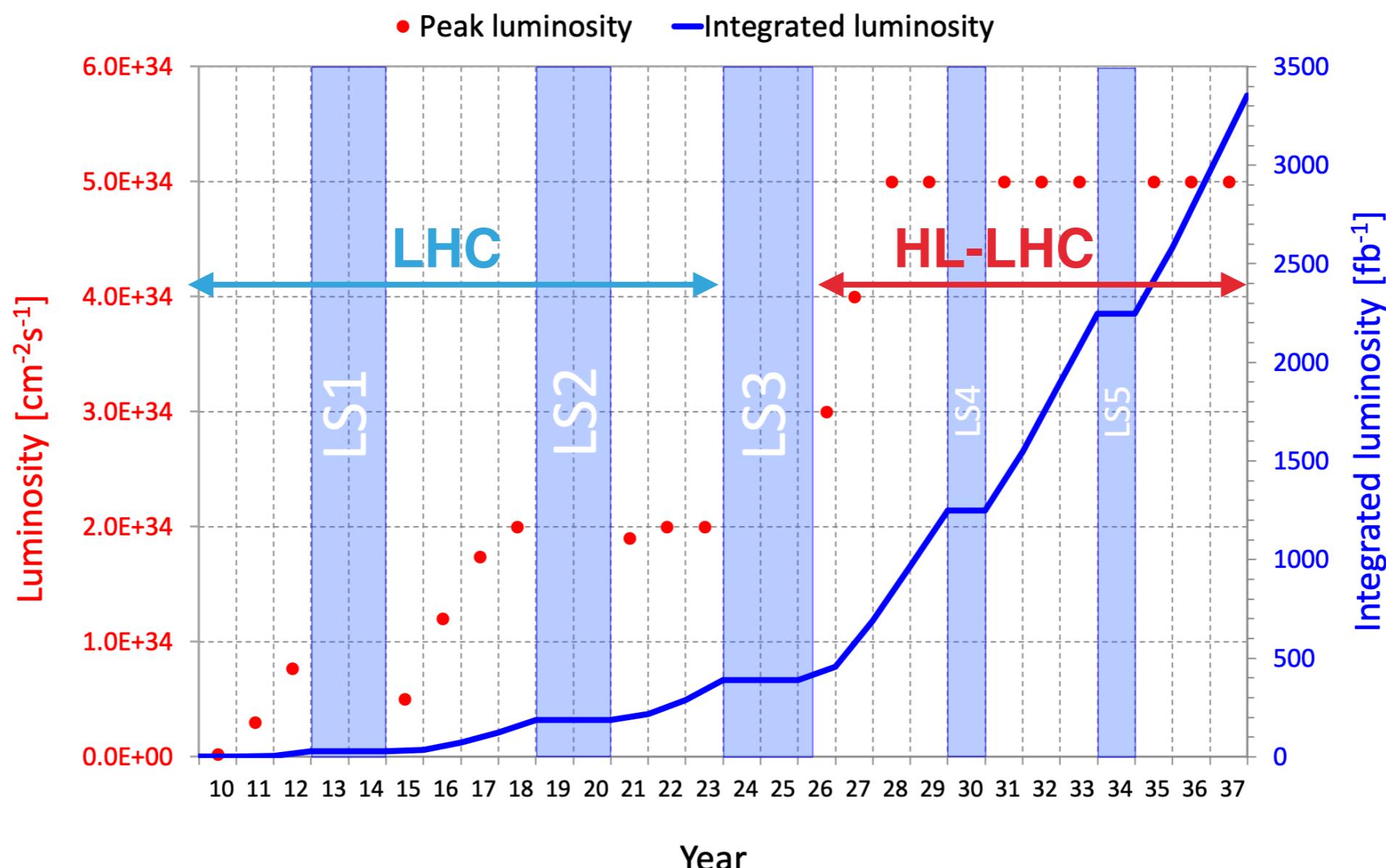
MARIA UBIALI

UNIVERSITY OF CAMBRIDGE

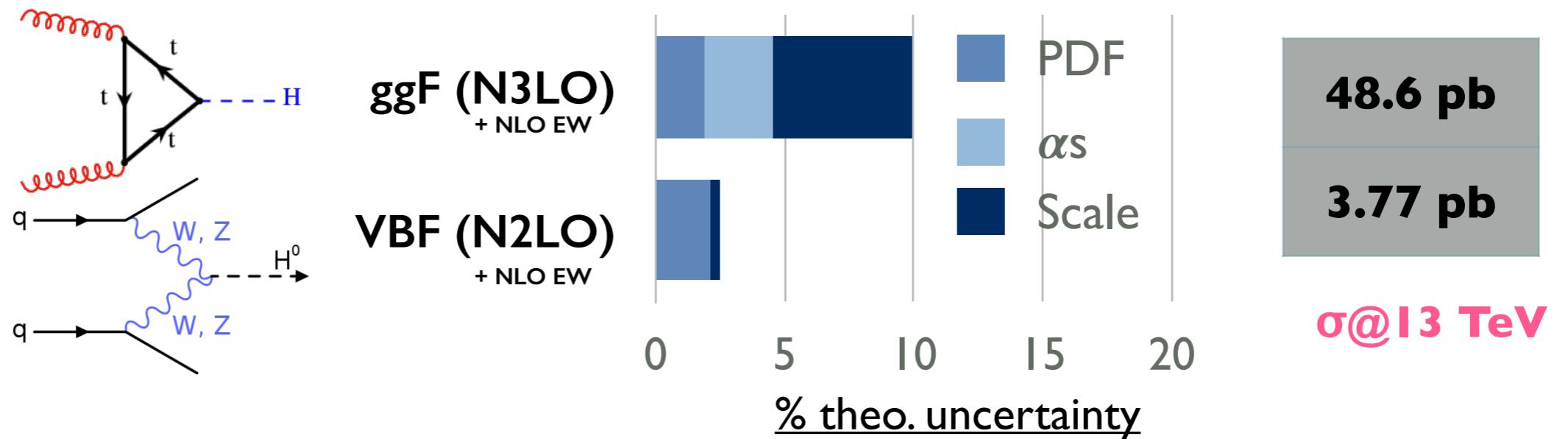
NEW FRONTIERS IN PDF ANALYSES IN THE HL-LHC ERA

PRECISION CHALLENGE AT THE HL-LHC

- With plethora of new data at HL-LHC and increased accuracy of experimental data, theoretical predictions face unprecedented precision challenge
- In this talk focus on PDFs, which are an essential element of any theoretical prediction at hadron colliders



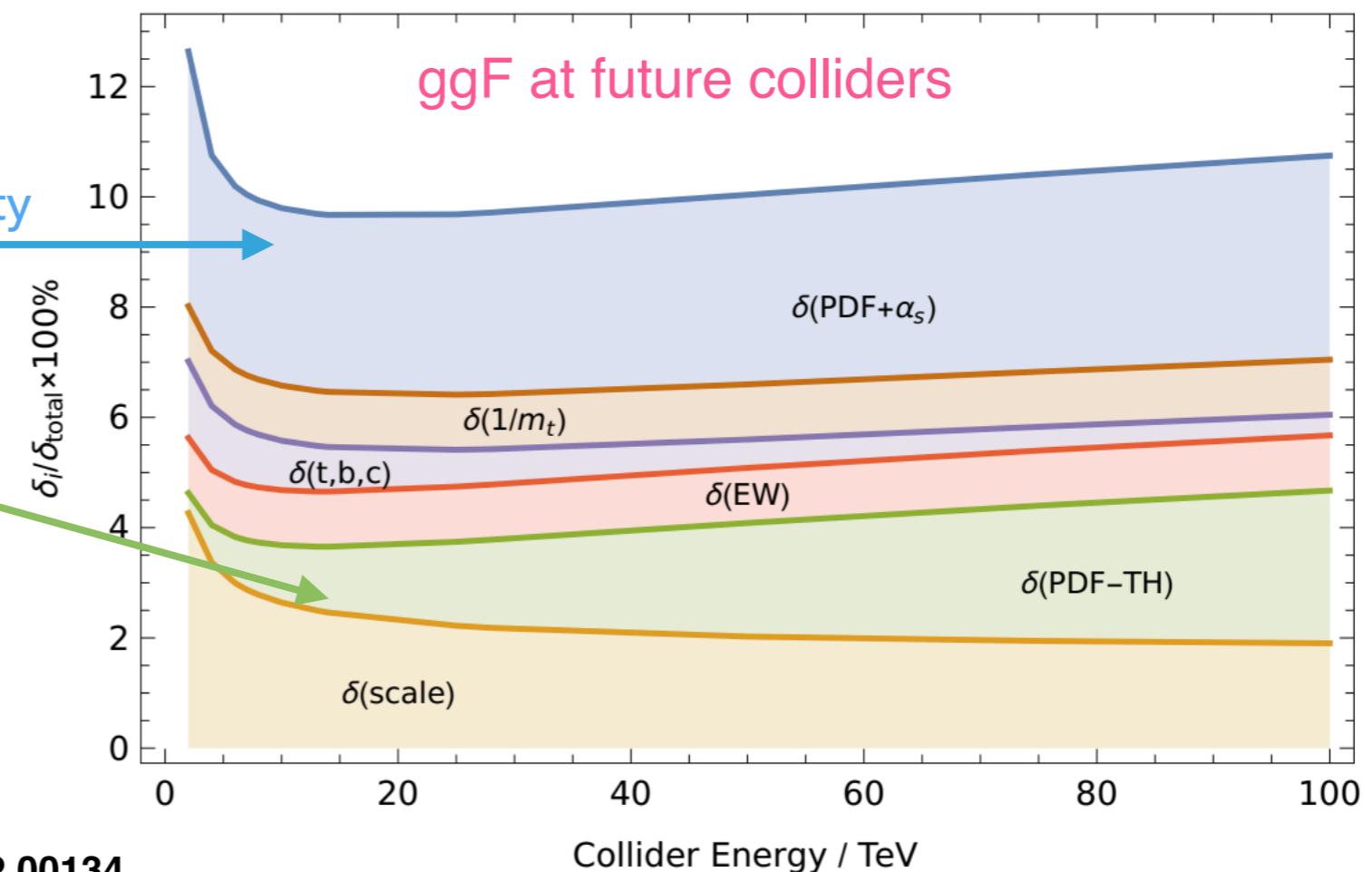
THE ROLE OF PDF UNCERTAINTIES



PDF uncertainty significantly limitation to theory accuracy

PDF+as uncertainty

Th. mismatch

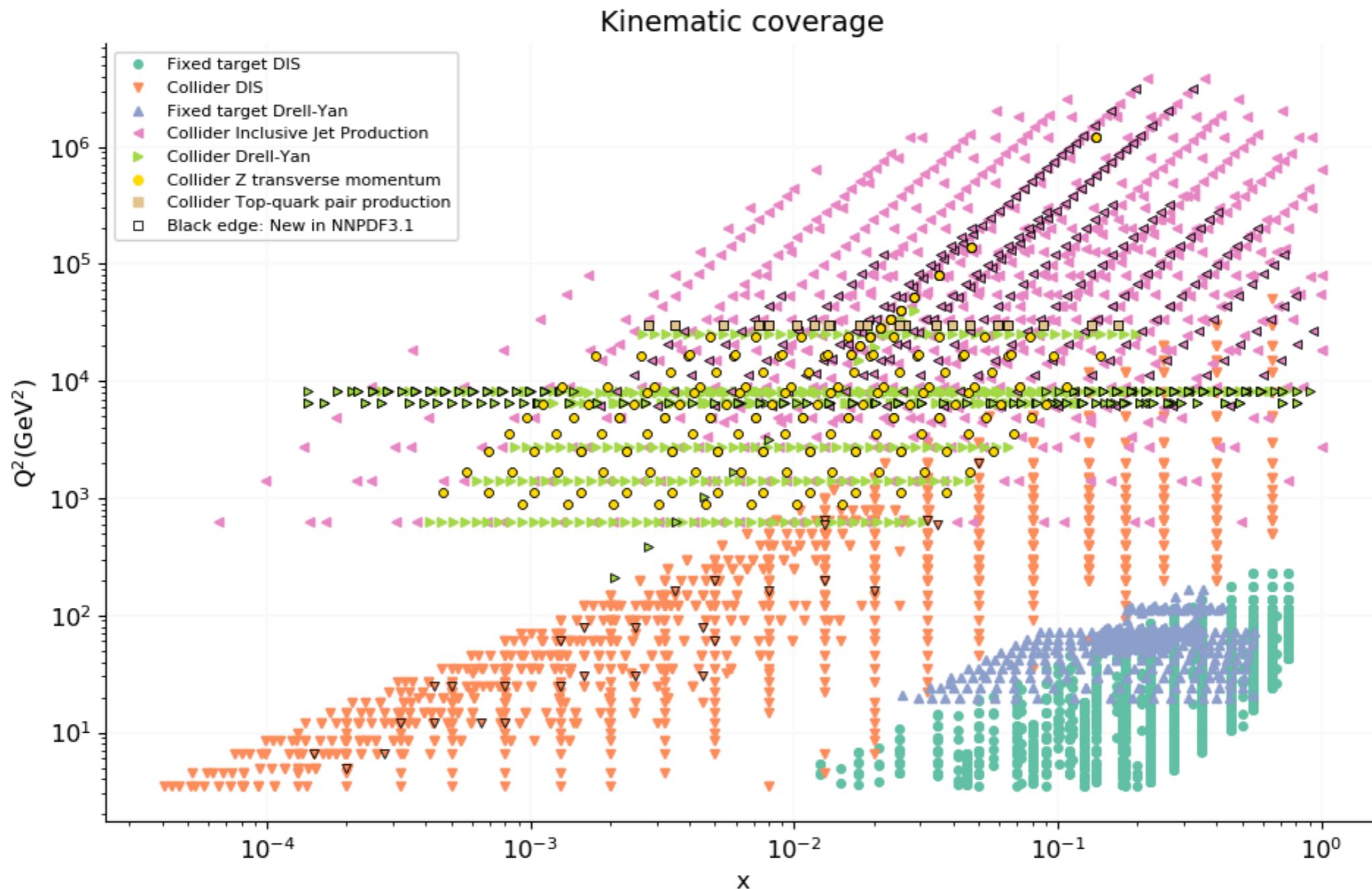


THE EXPERIMENTAL DATA

$$f_i(x, \mu) \pm \Delta_i(x, \mu)$$

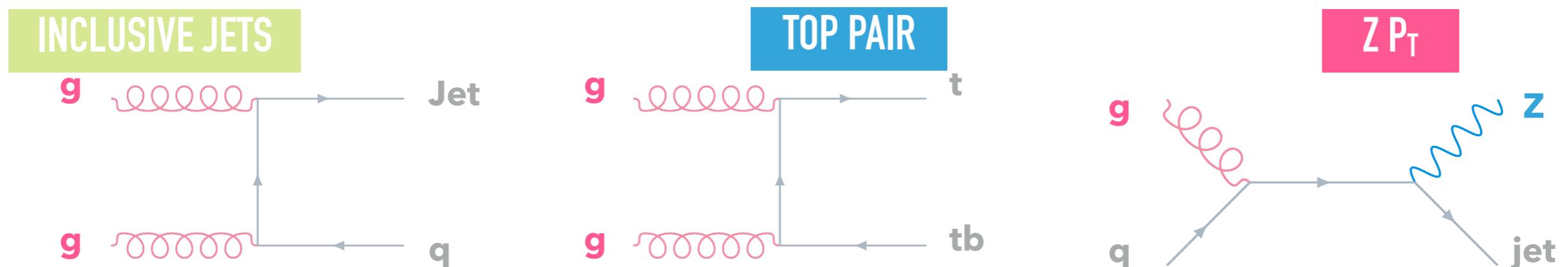
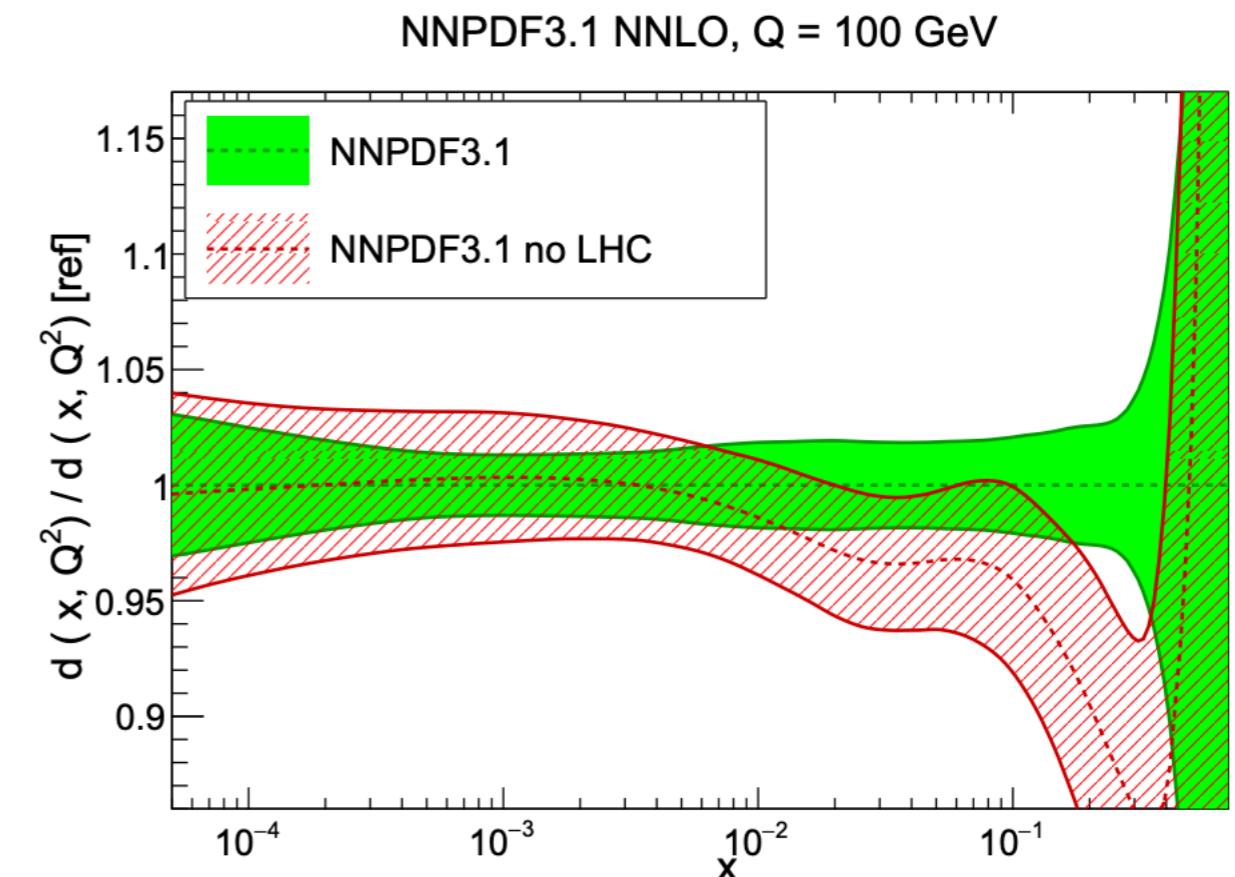
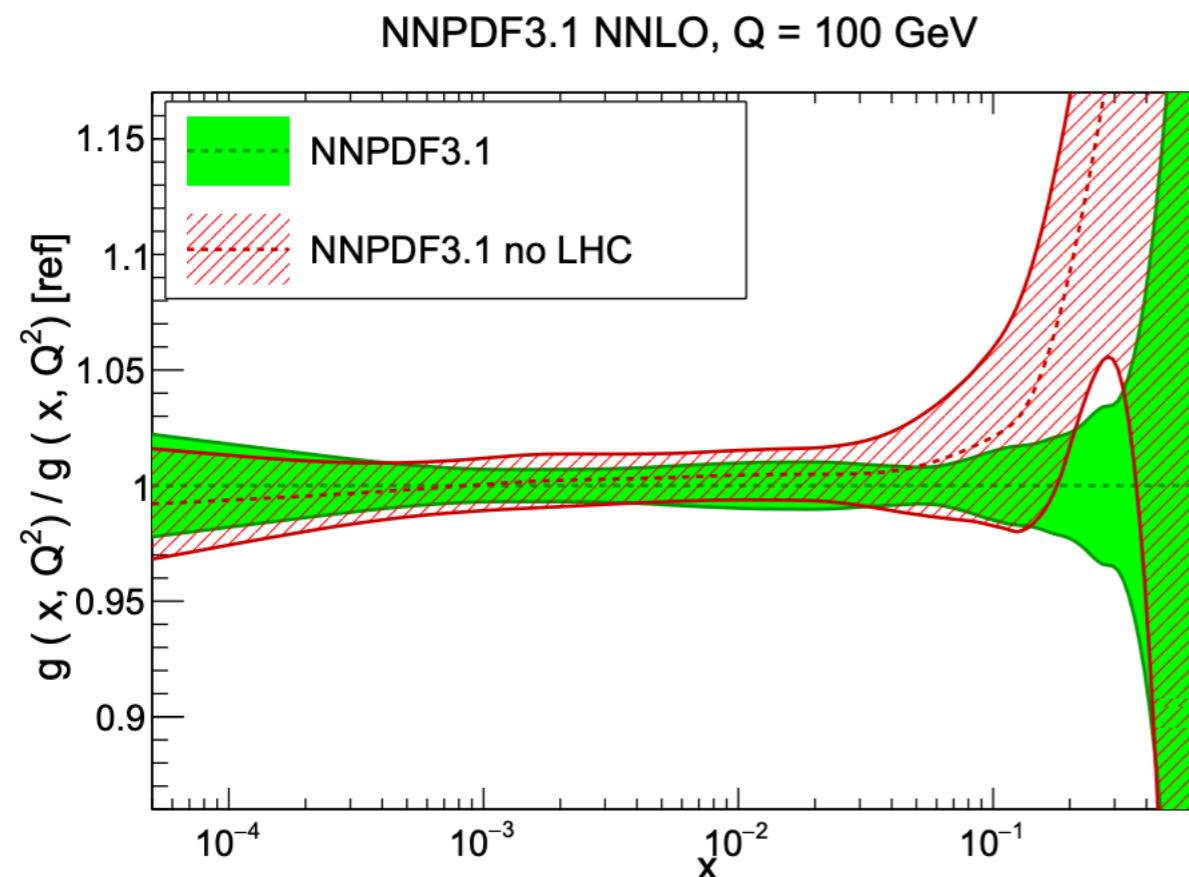
Fit to global set of data

Perturbative QCD
DGLAP evolution equations

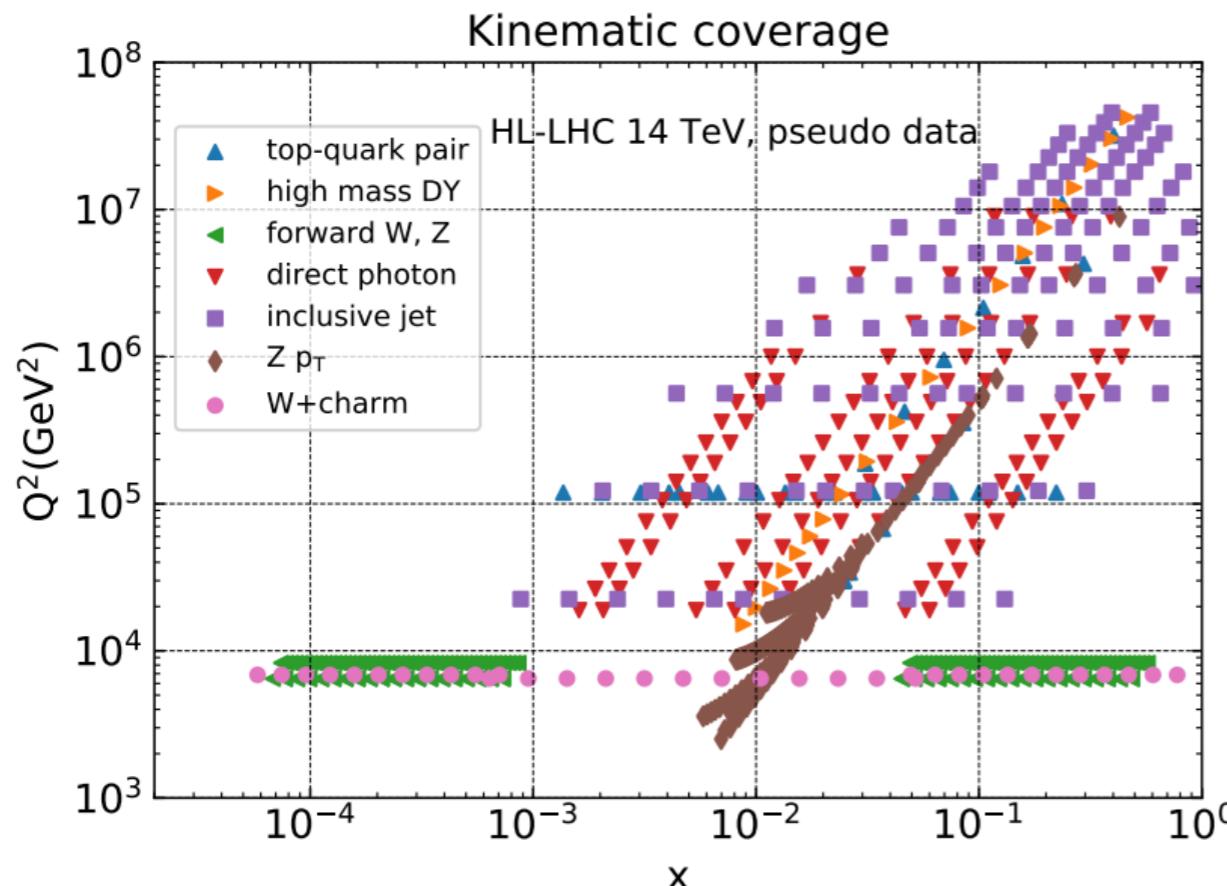


IMPACT OF THE LHC DATA - GLUON PDF

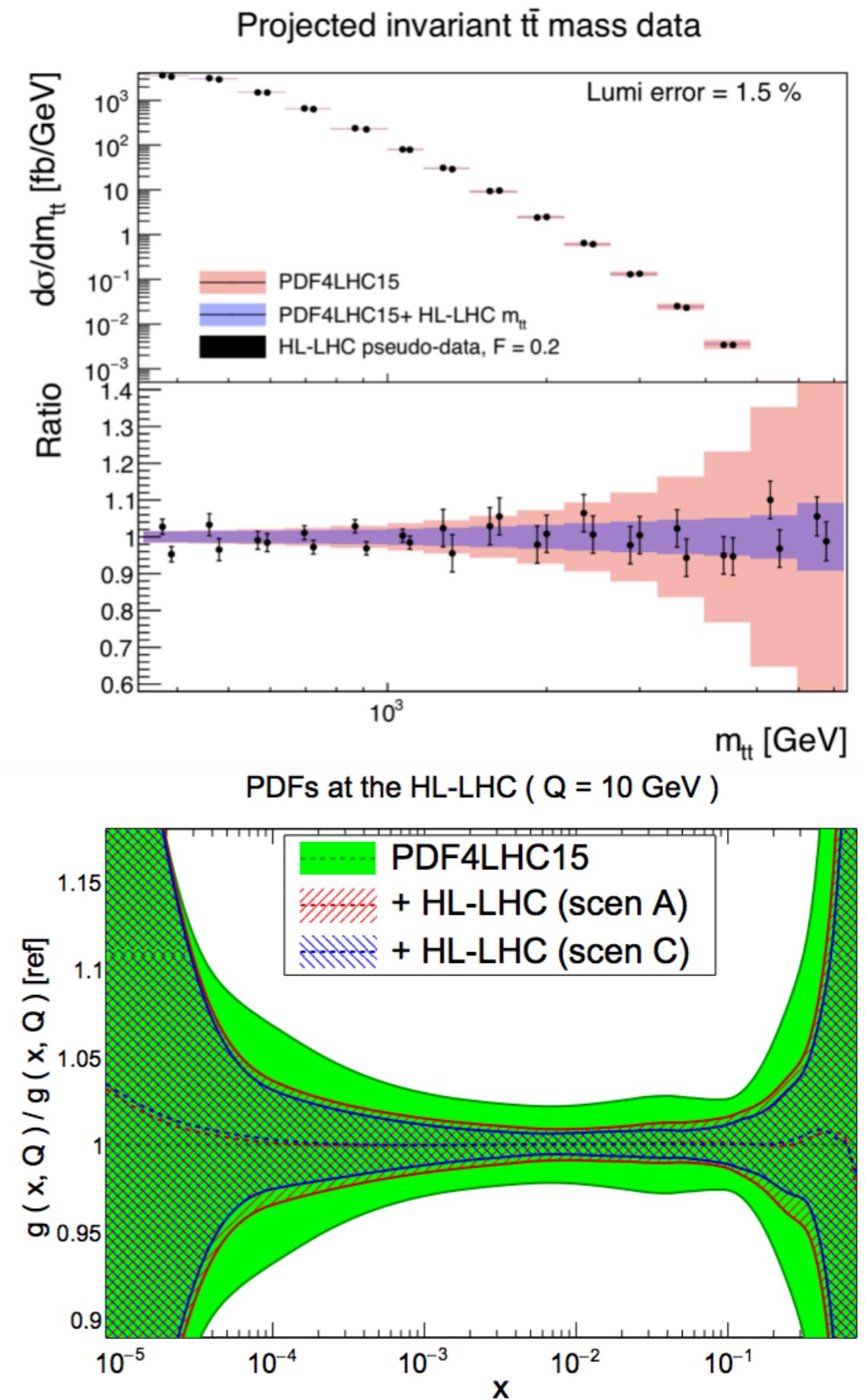
- Inclusion of LHC data reduces PDF uncertainties and has a significant pull at medium large- x
- Large- x gluon constrained by (at least) three independent processes, see a consistent picture



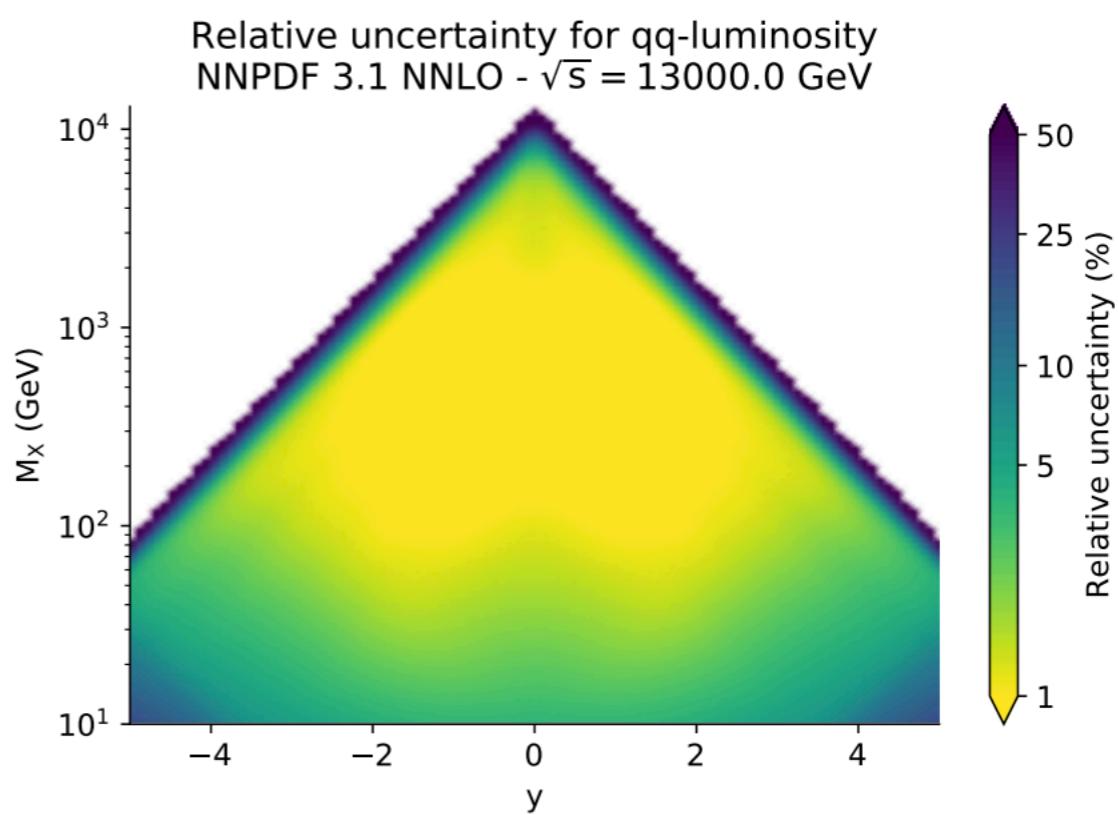
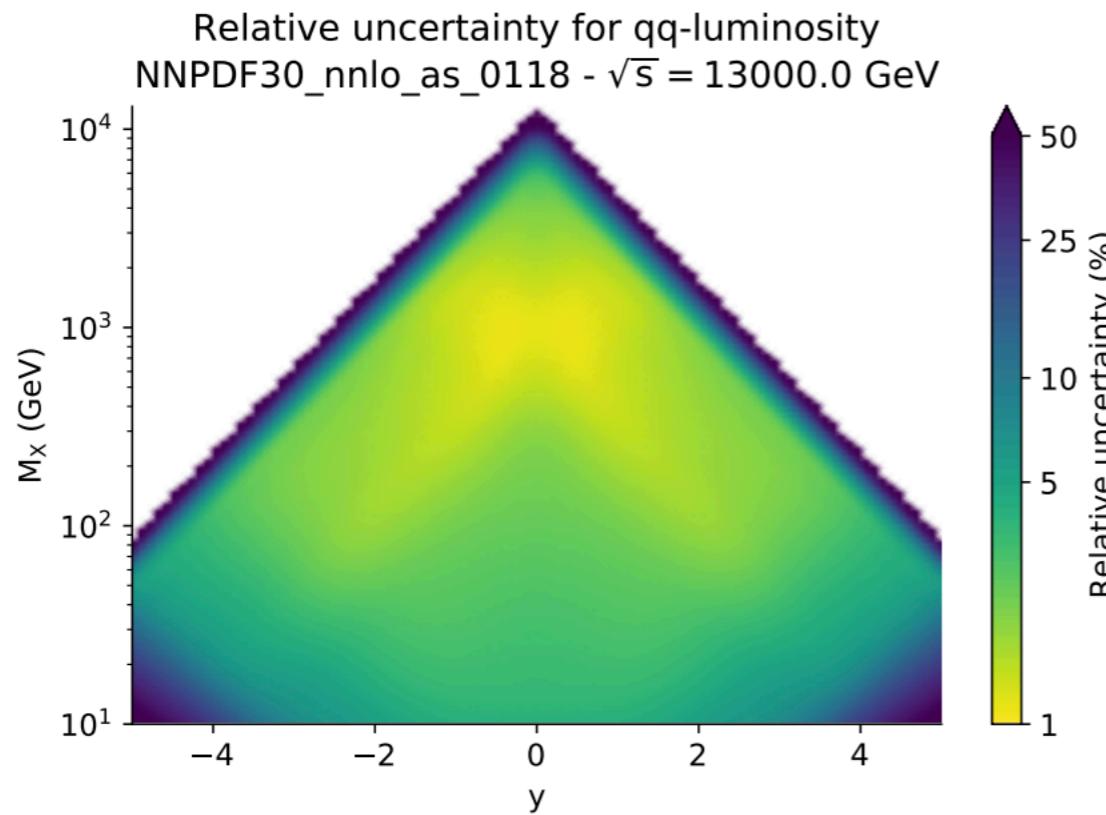
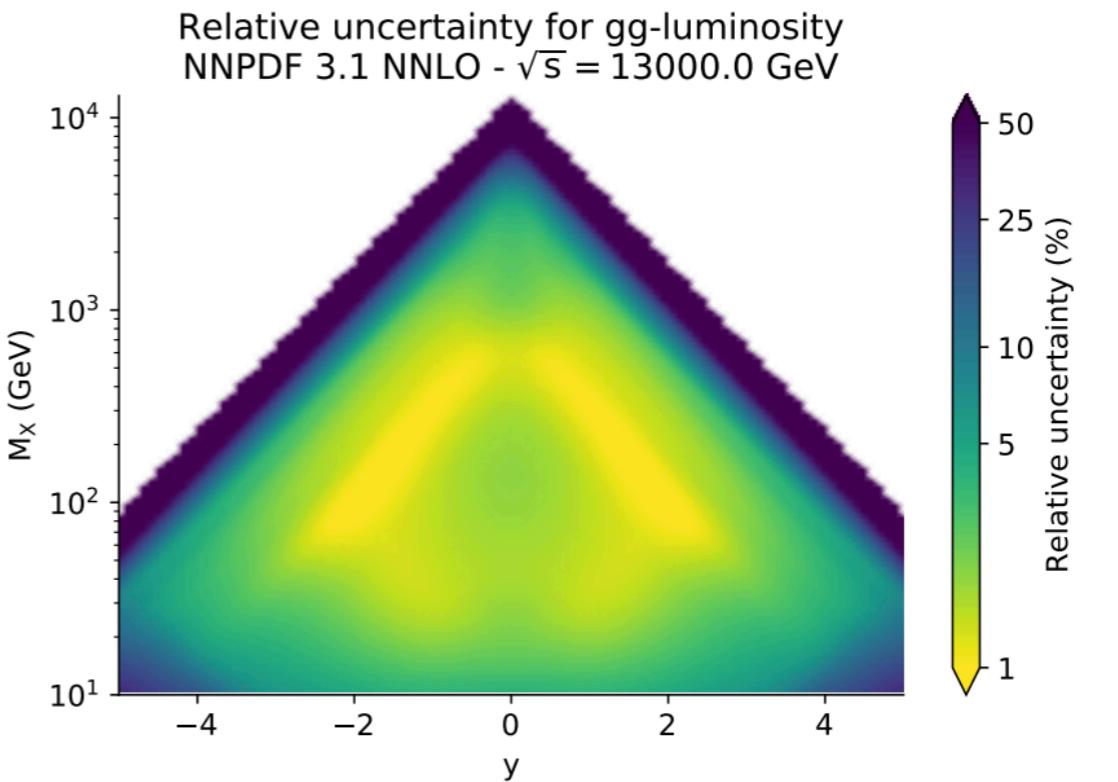
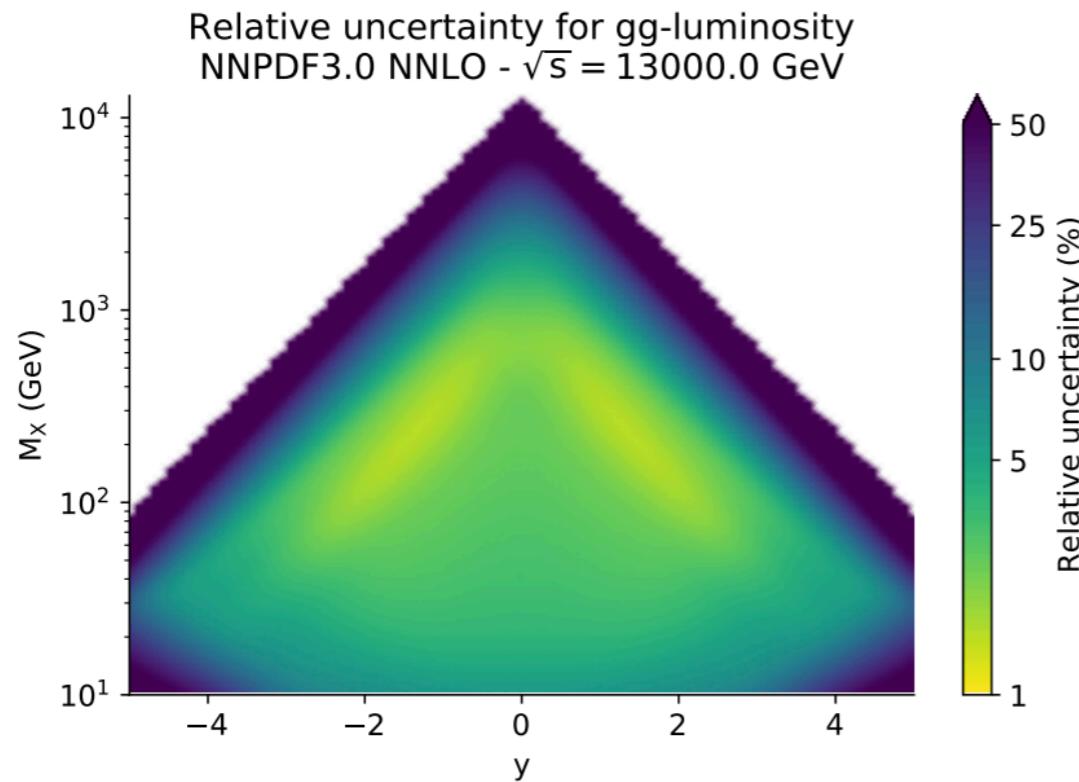
PERSPECTIVES AT HL-LHC



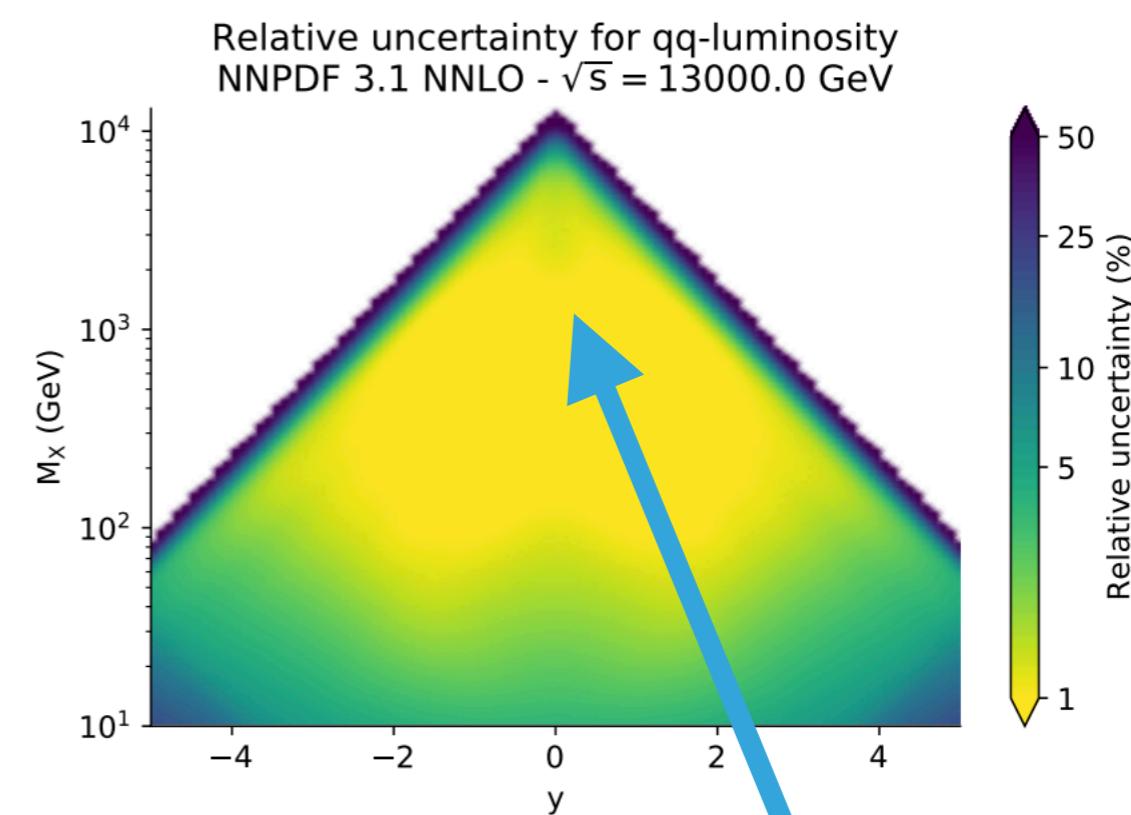
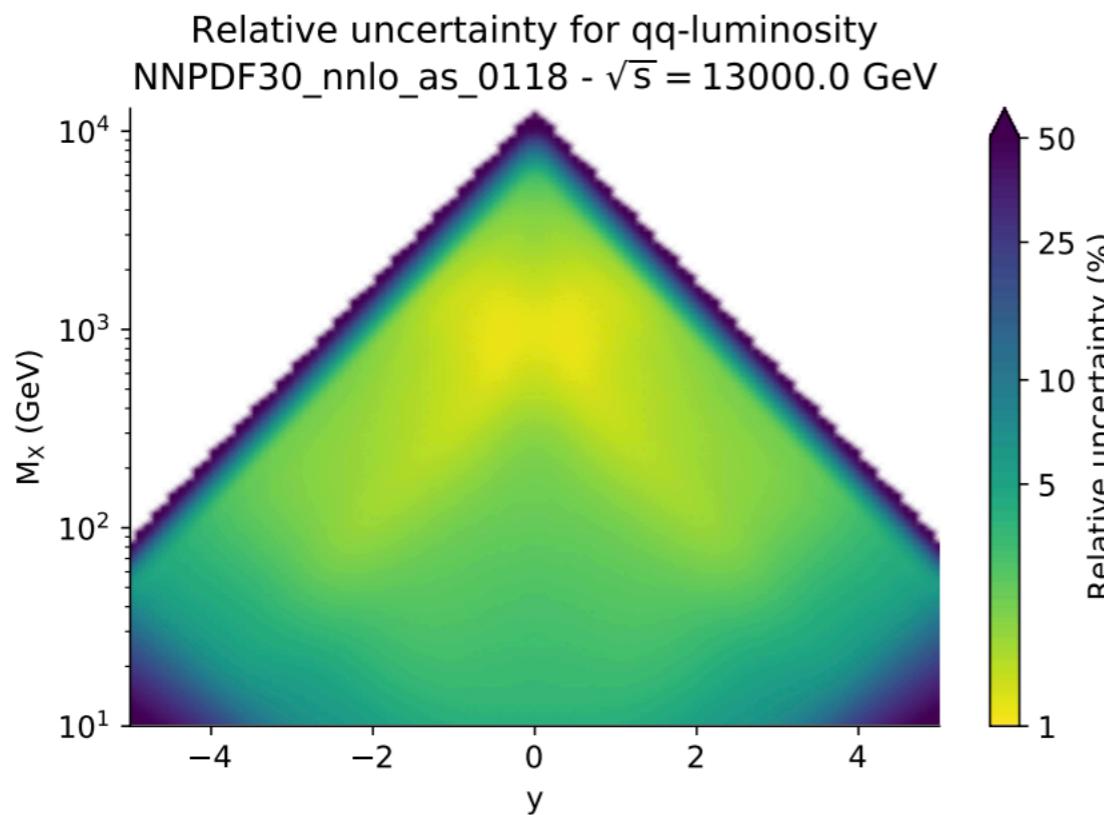
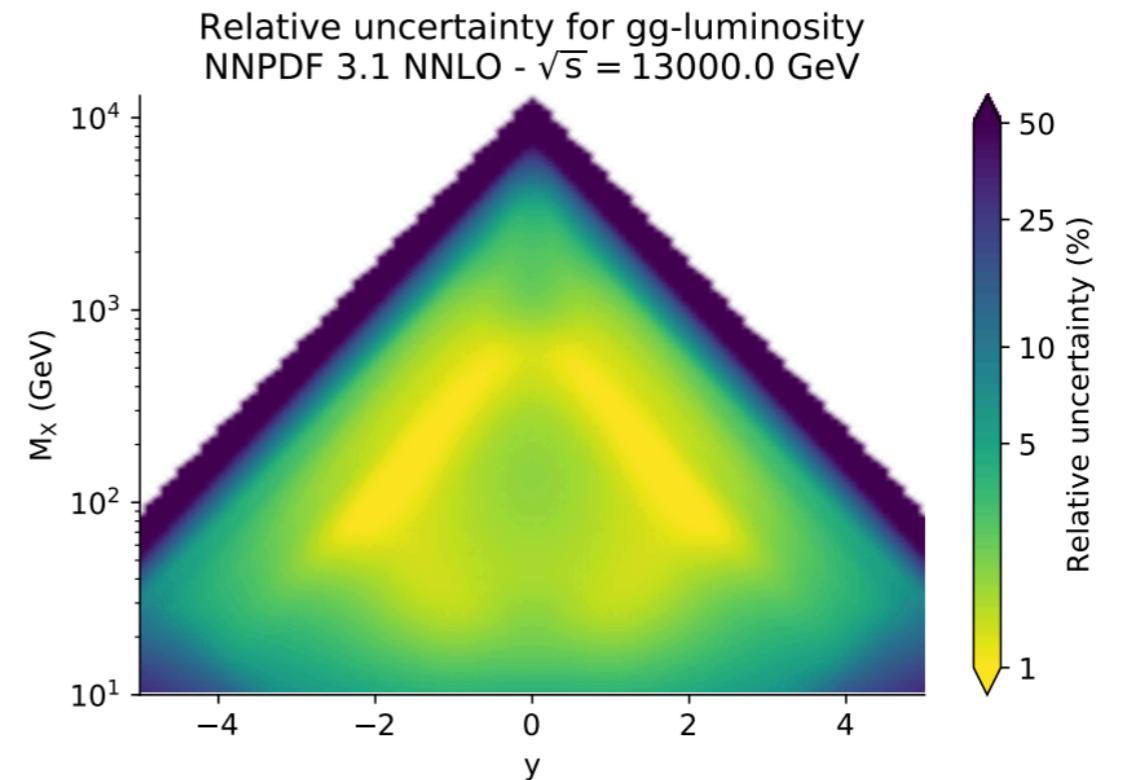
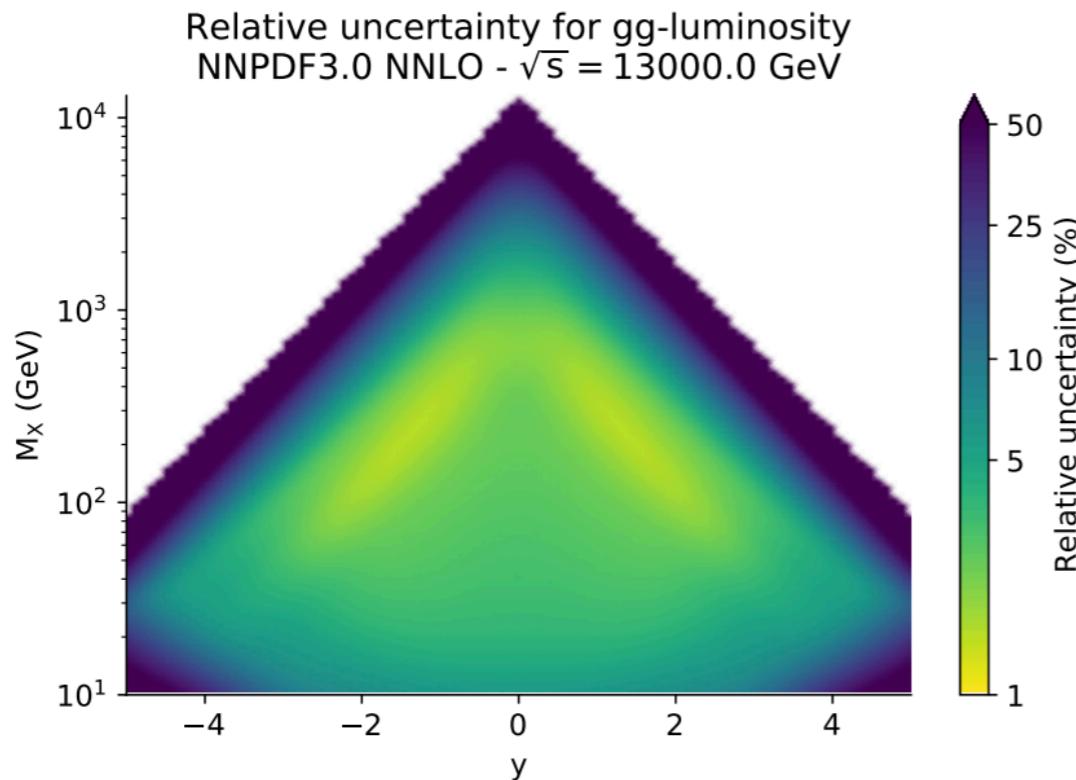
- W, Z handle on quarks
- W+c on strangeness
- Z pT on quarks and gluons
- Top and Jets on gluons



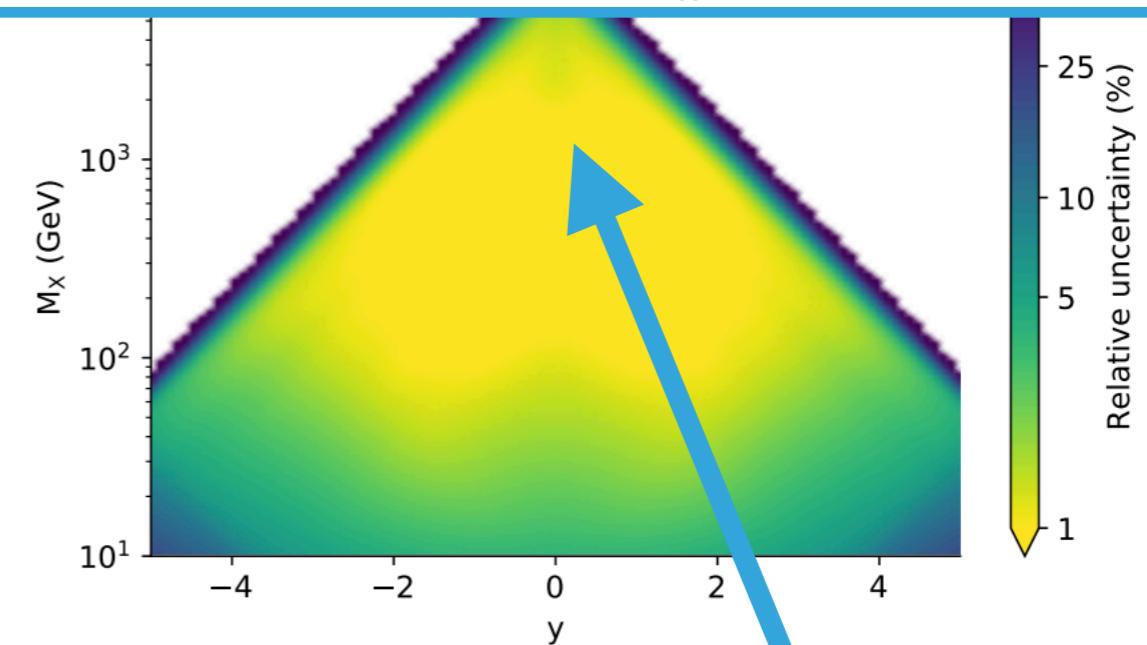
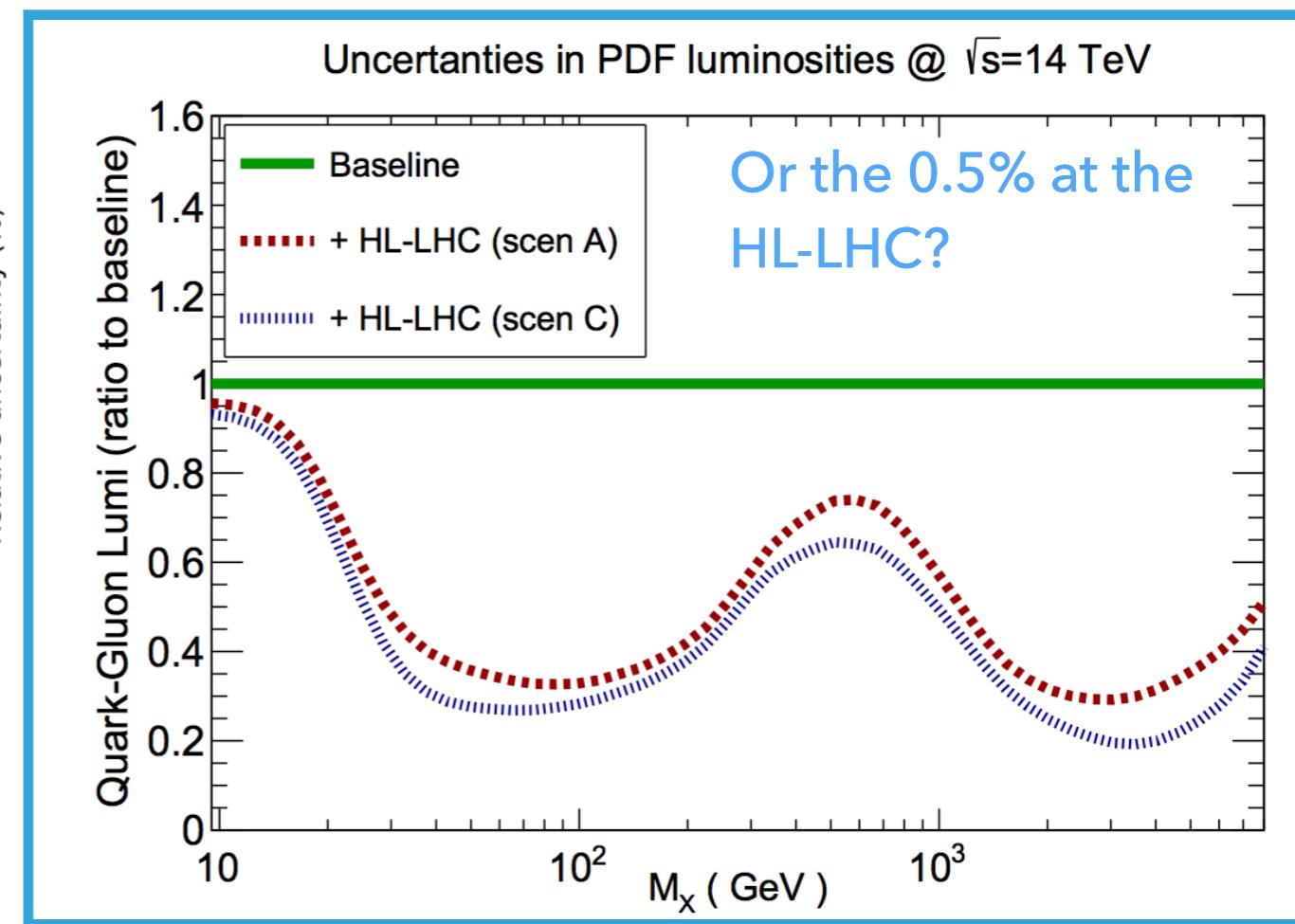
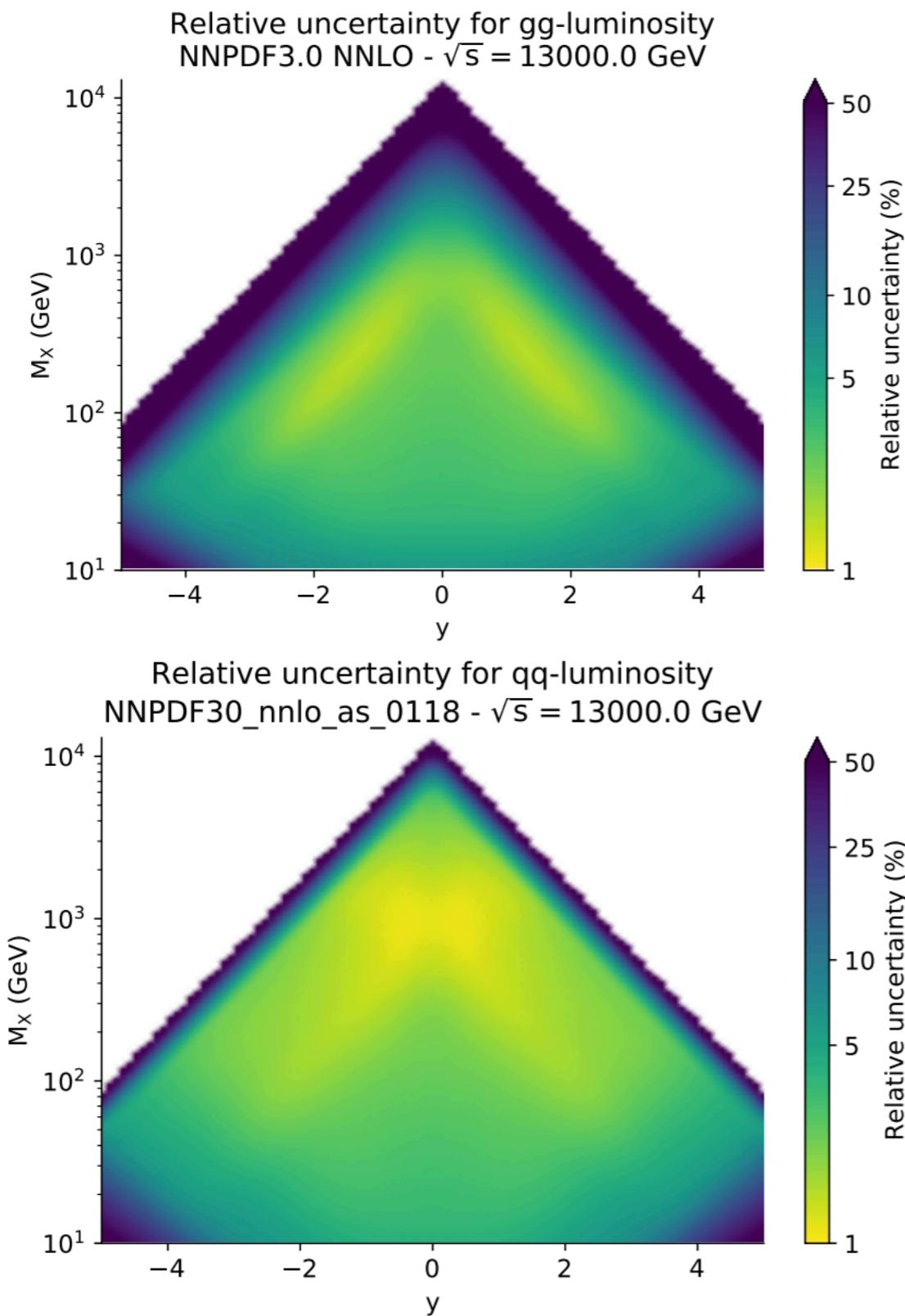
THE PRECISION CHALLENGE



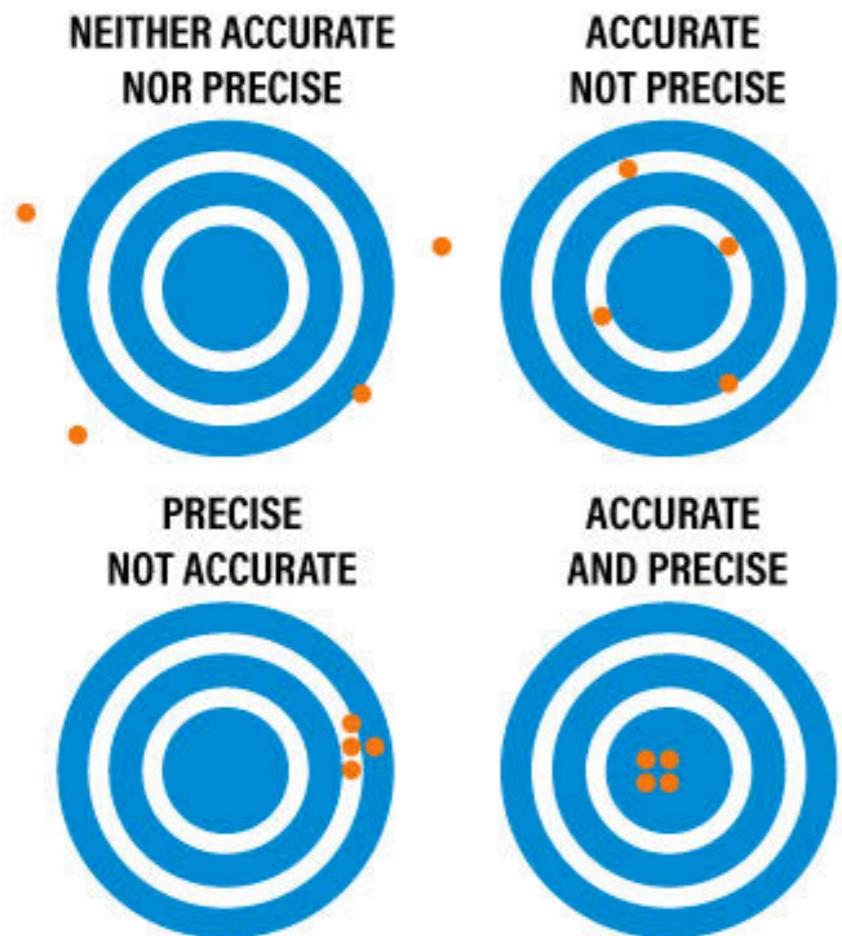
THE PRECISION CHALLENGE



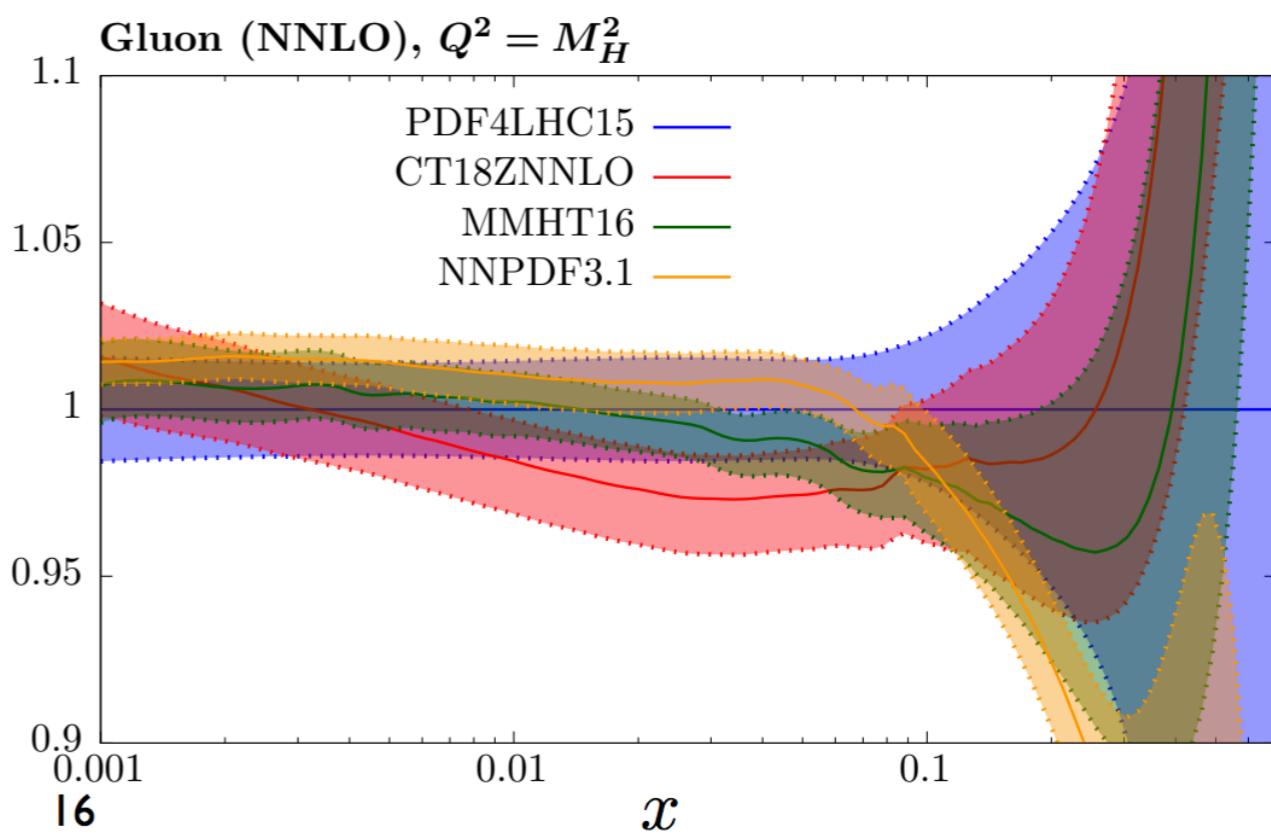
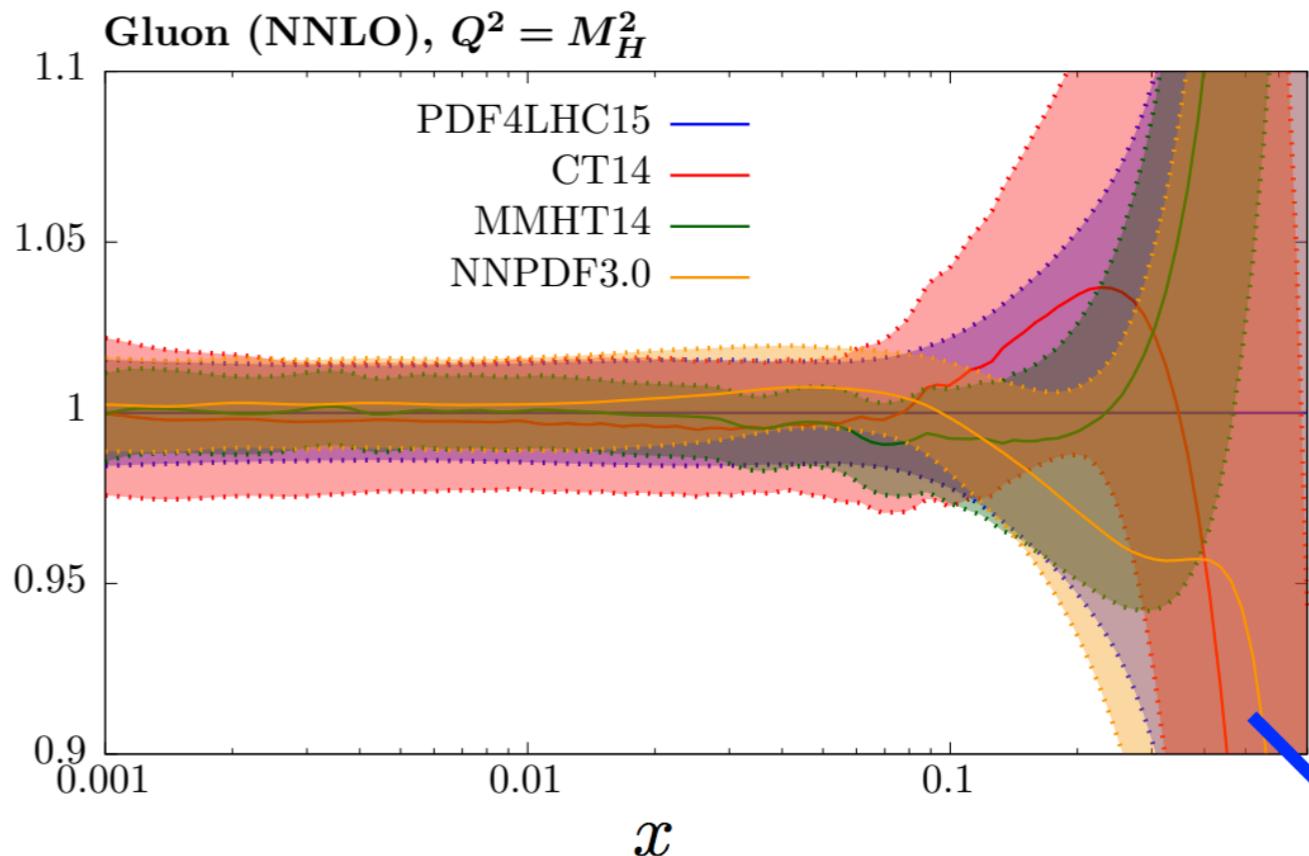
THE PRECISION CHALLENGE



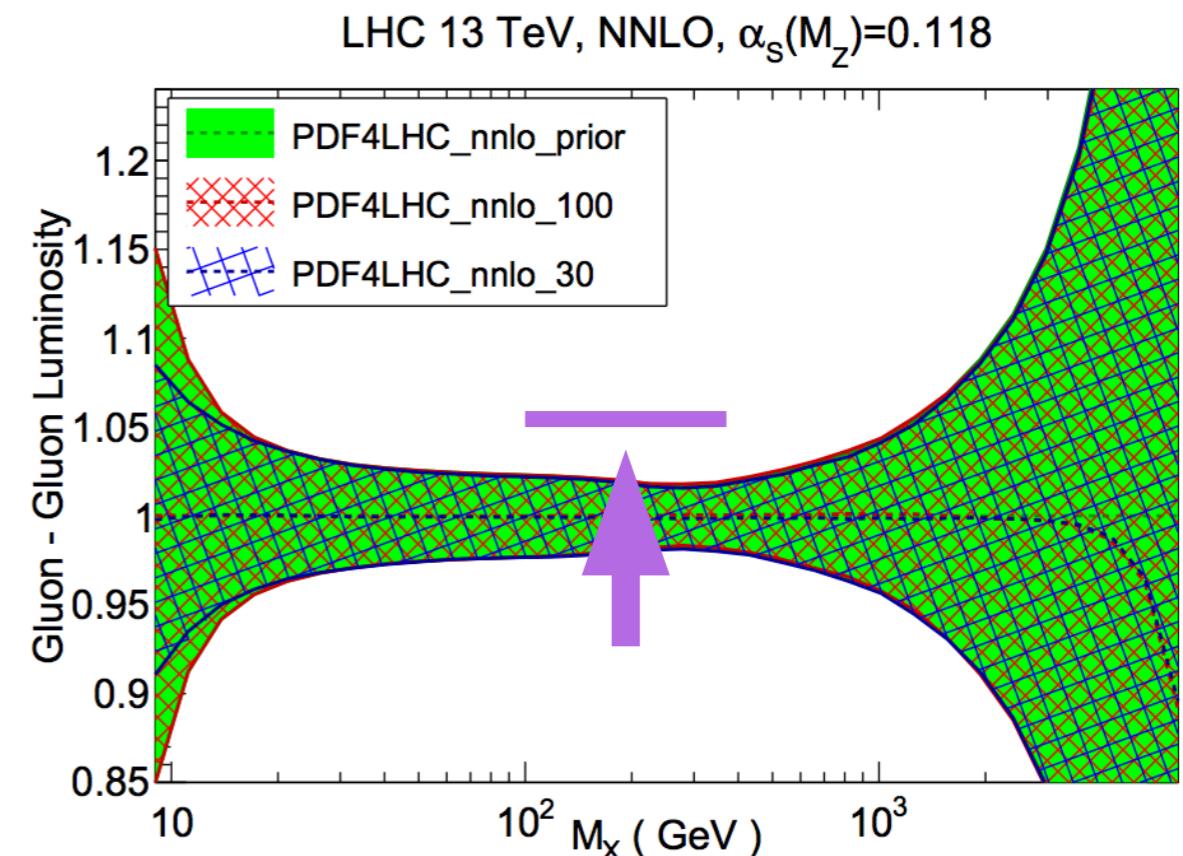
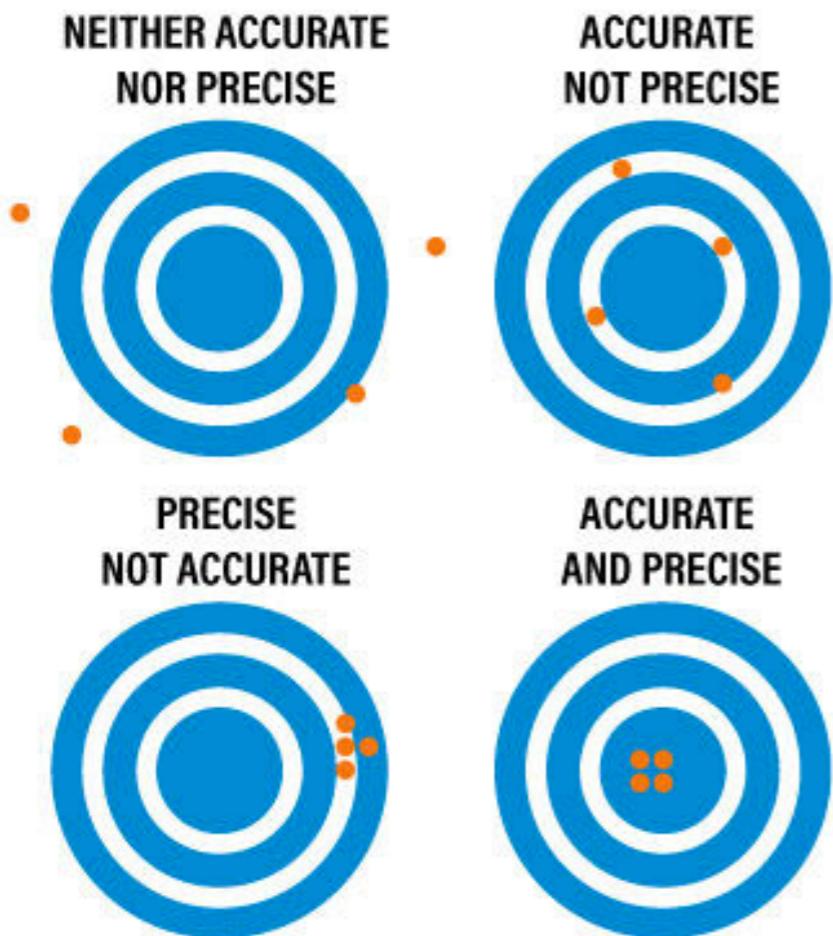
THE PRECISION VS ACCURACY CHALLENGE



- CT18, "MMHT"2020 and NNPDF3.1 based on comparable data sets. Preliminary comparison of PDF sets suggests that differences among sets increased compared to 2015 combination
=> **ONGOING BENCHMARKING**
(J. Rojo's talk at PDF4LHC)

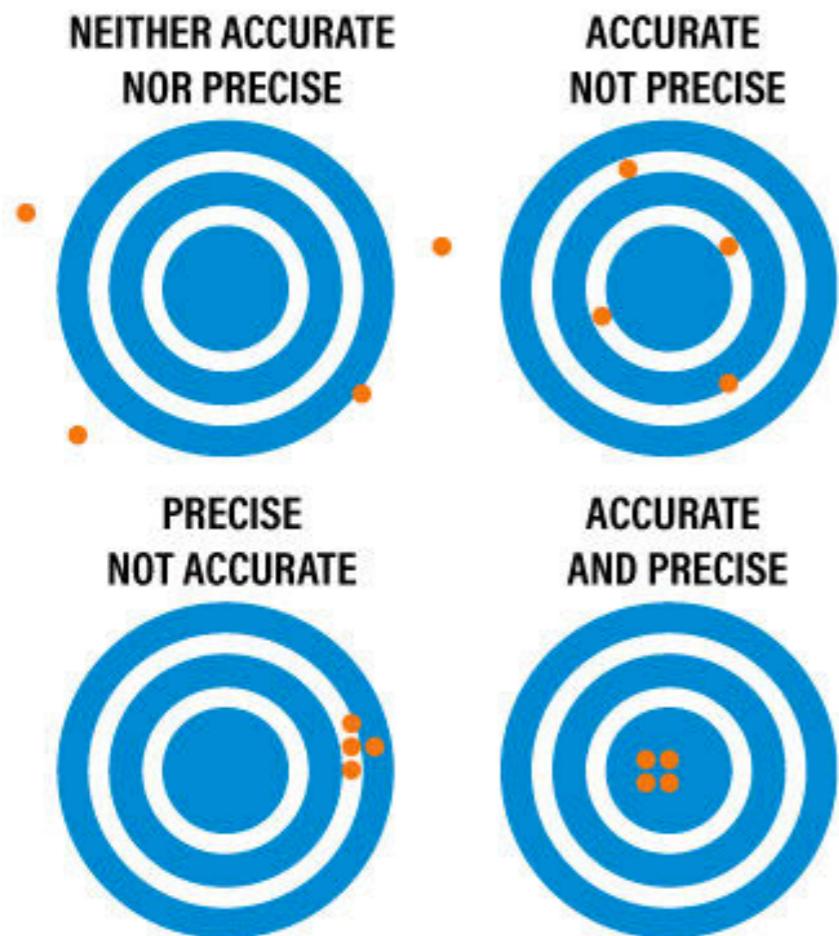


THE PRECISION VS ACCURACY CHALLENGE

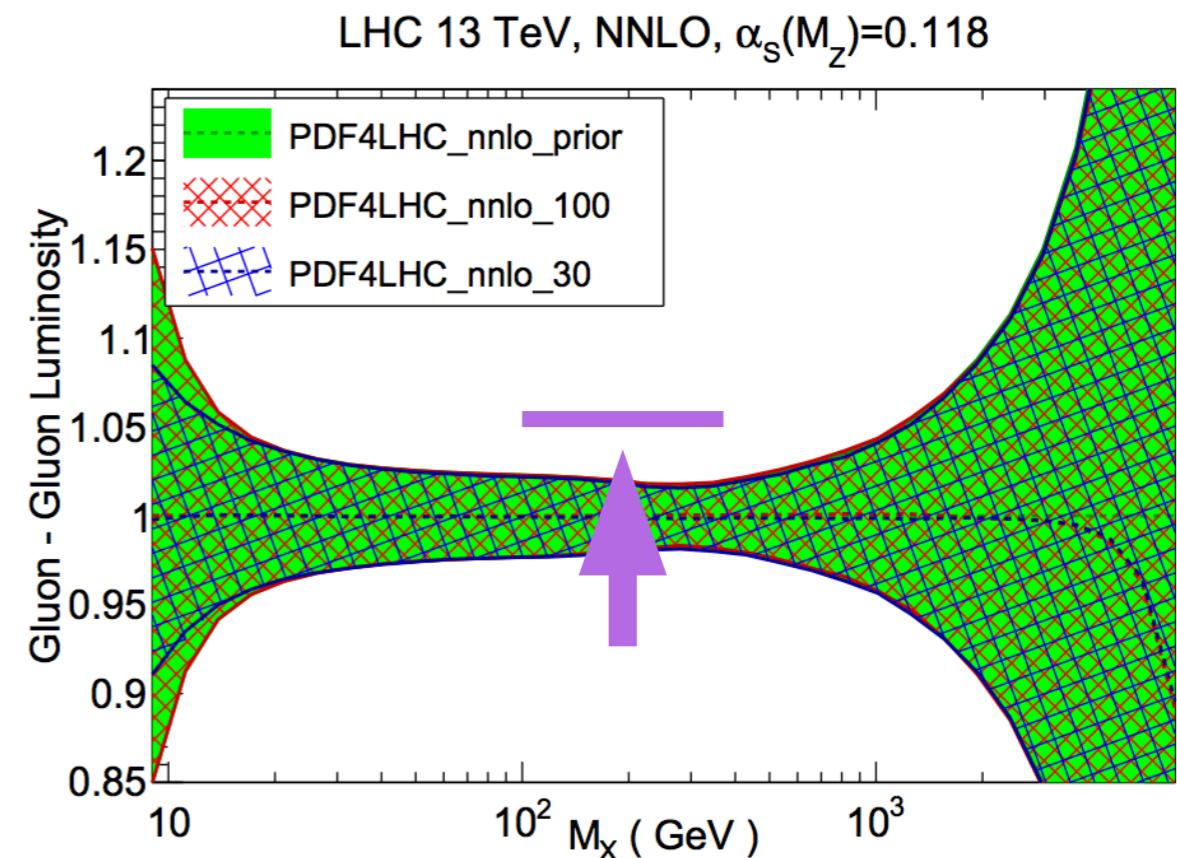


- Take one PDF analysis at the time, take an updated analysis. What happens if shift between old and new set are much larger than PDF uncertainties of previous analysis?

THE PRECISION VS ACCURACY CHALLENGE



- Take one PDF analysis at the time, take an updated analysis. What happens if shift between old and new set are much larger than PDF uncertainties of previous analysis?

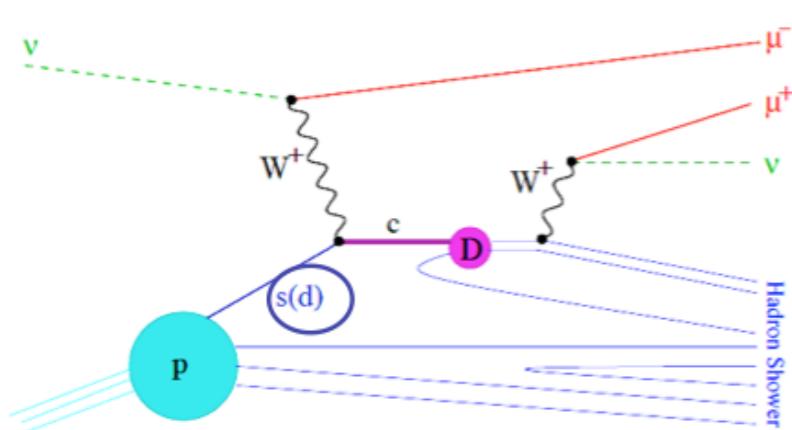


- ▶ Experimental data:
 - Inconsistency or tension
 - Highly correlated data
- ▶ Methodology:
 - Data-driven parametrisation change
 - Improvements in fitting methodology/minimisation
- ▶ Theoretical framework
 - Missing higher order uncertainties
 - BSM effects
 - Other corrections (nuclear)

INCONSISTENCY OR TENSION IN DATA

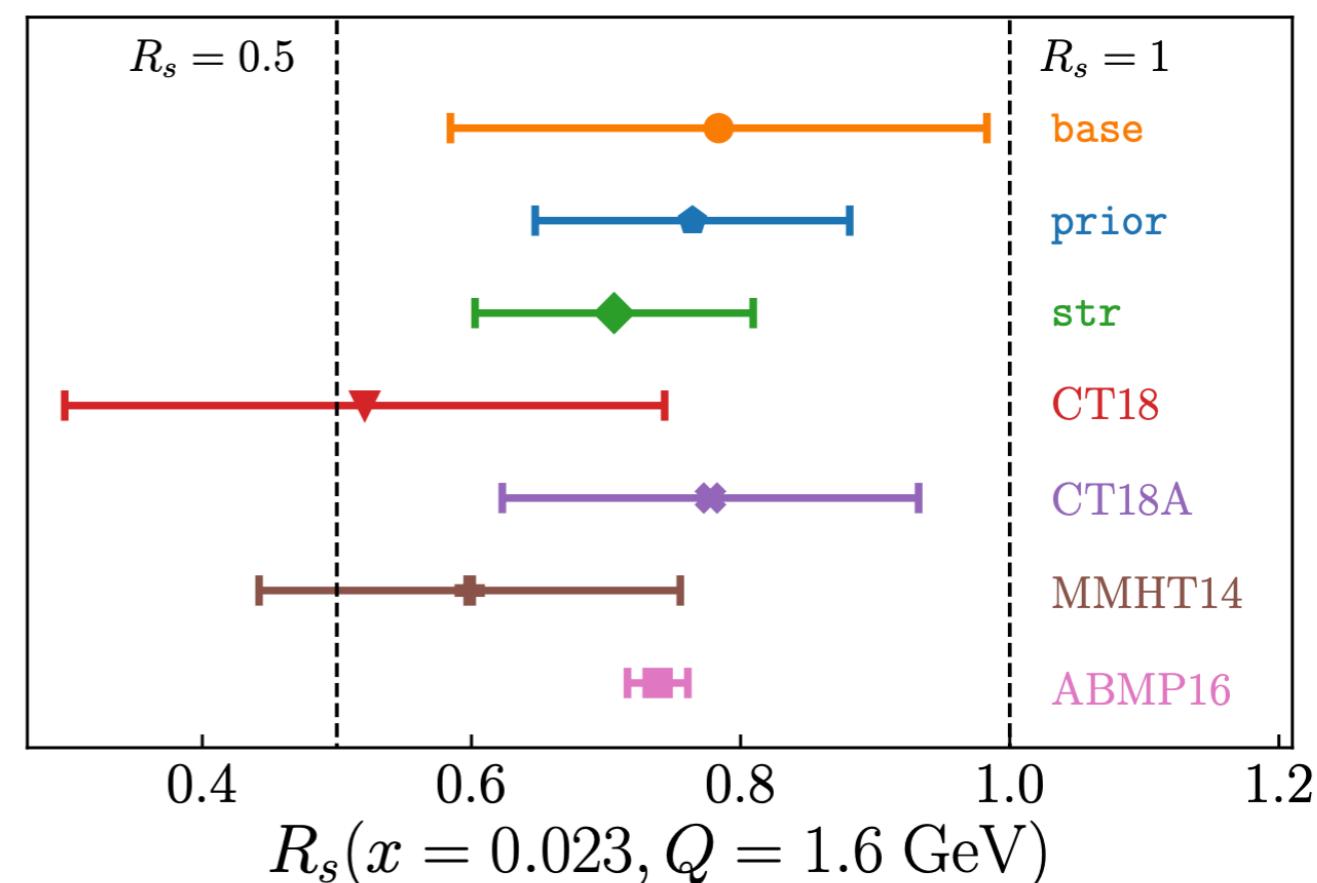
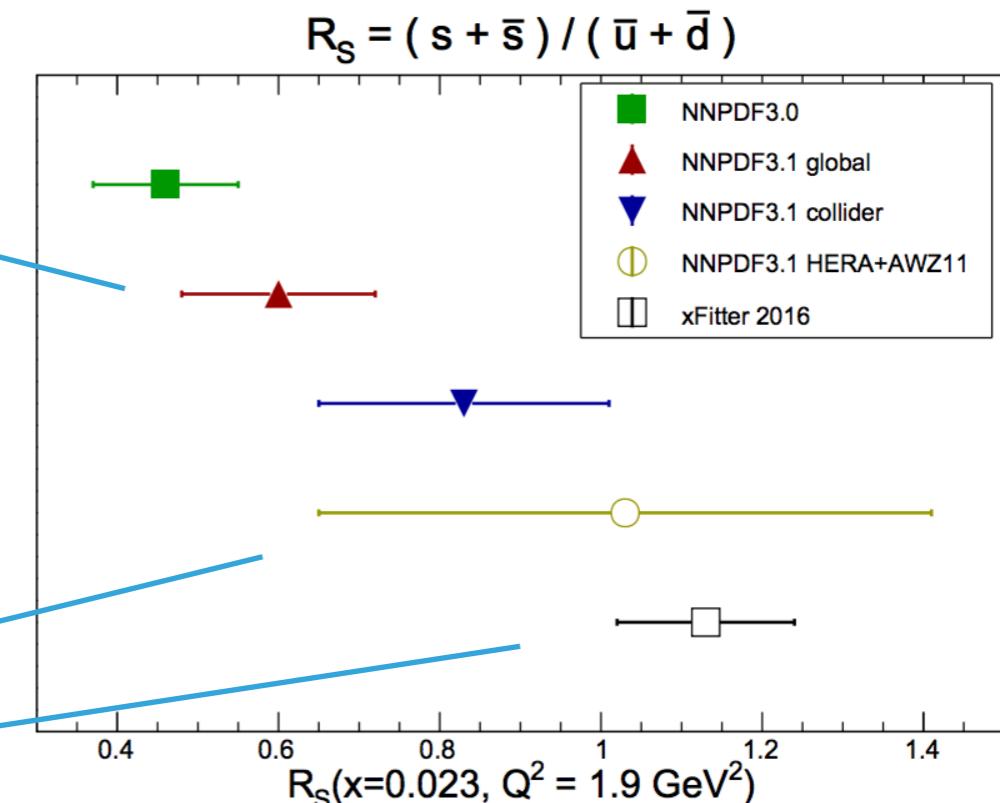
Ball et al, EPJC 77 (2017)

Dominated by NuTeV data



Both include HERA & LHC
precise W/Z data but use
different parametrisation
and methodologies

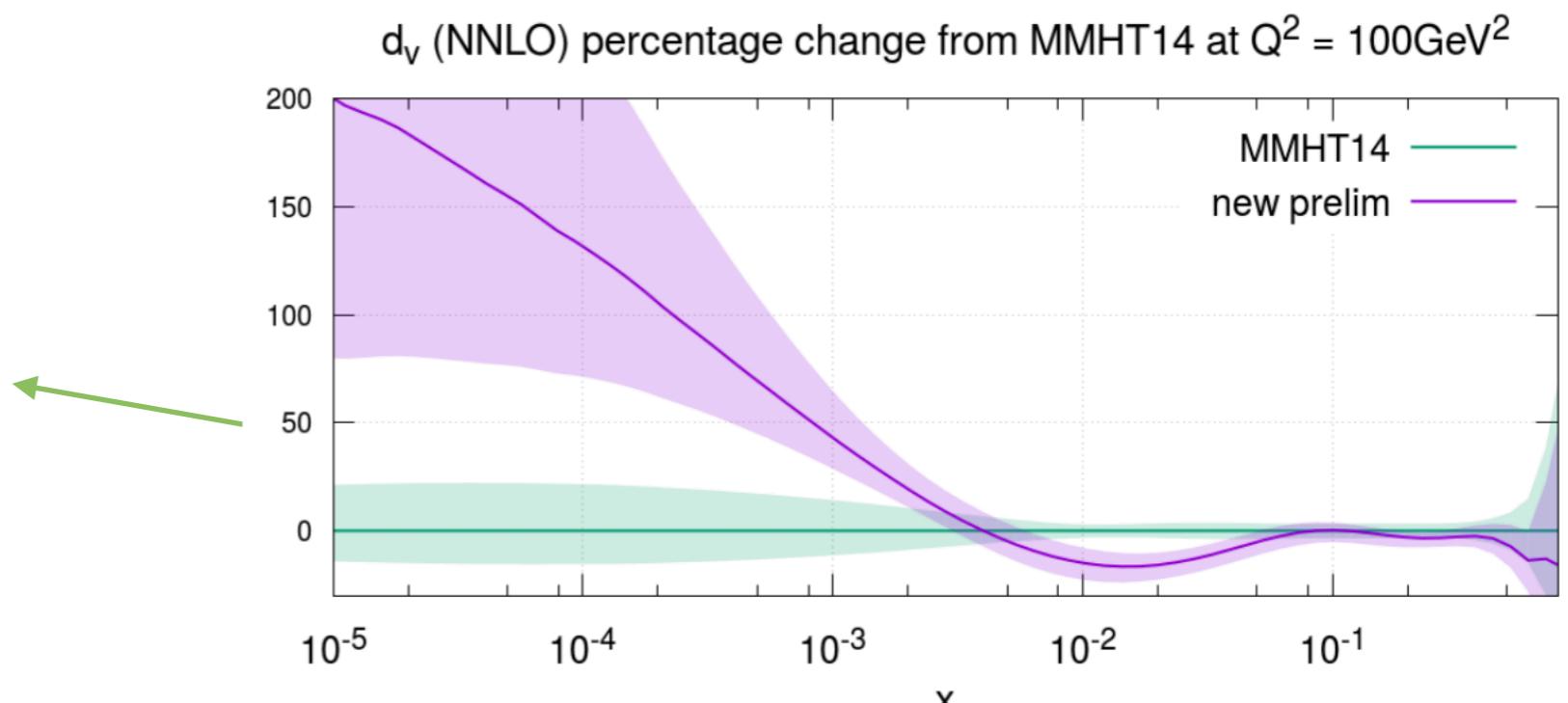
With the Inclusion of all strange-sensitive measurements in a global fit (NuTeV and NOMAD DIS, LHC W,Z, ATLAS and CMS W+c production at 7 and 13 TeV) tension vanishes
[Faura, Iranipour, Nocera, Rojo, MU 2009.00014]



METHODOLOGY: PARAMETRISATION

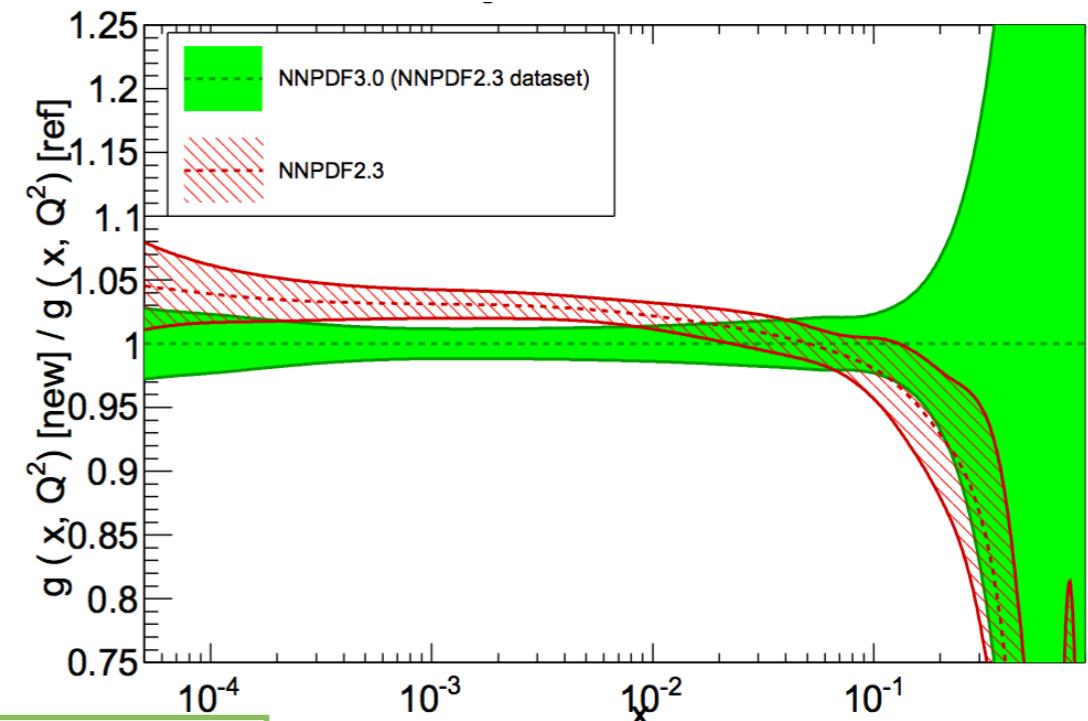
"MMHT"2020 analysis: Extended parametrisation of PDFs based on Chebyshev polynomials.
Down valence quark changes quite dramatically and reduces tension among data

R. Thorne, PDF4LHC September 2019



METHODOLOGY: FIT AND MINIMISATION

NNPDF2.3 to 3.0 shift
due to change in
methodology!



Try harder!

New Fitting Methodology

Define Underlying Physical Law
ie input PDFs from MSTW08, CT10, NNPDF2.3...

Generate random pseudo-data for the NNPDF3.0 dataset
from info of experimental uncertainties and correlations

Perform (NN)PDF fit

Validate resulting PDF set:
 Reproduce input PDFs
 Both central values and uncertainties
 Expected values of χ^2 are determined by pseudo-data
 PDF reweighting equal to refitting (Bayesian inference)

Now you can fit
real exp data!

Closure Test
successful!

OK!

Fail?

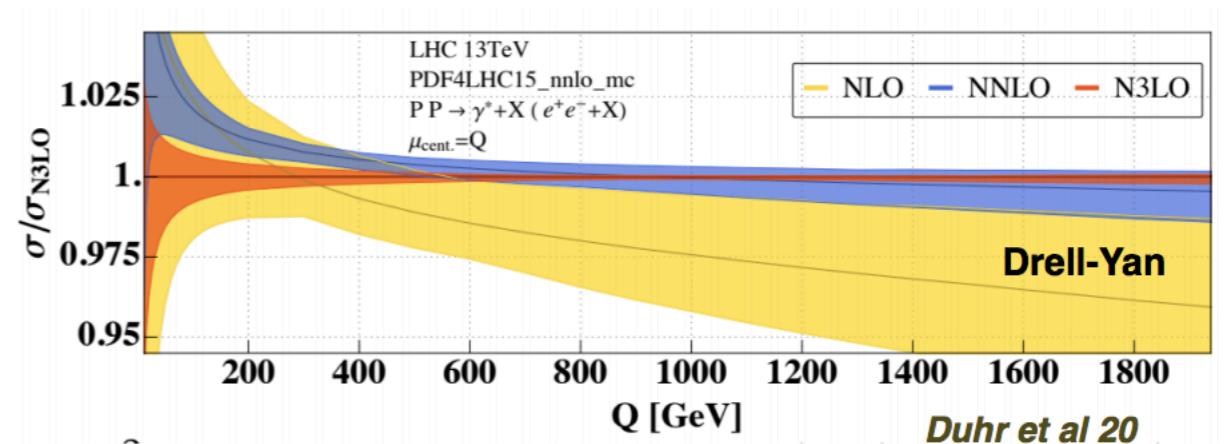
Crucial for PDF
methodology to be
validated by closure
test!

MISSING HIGHER ORDER UNCERTAINTIES

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

- ▶ Standard global PDF fits based on fixed-order NNLO QCD calculations
- ▶ **N3LO is now the precision frontier for theoretical predictions in PDF fits**

- N3LO splitting functions and DIS coefficient functions available but not yet implemented in evolution codes.
- N3LO partonic cross sections not yet available for most pp processes (apart from Drell-Yan) but some approximations available.



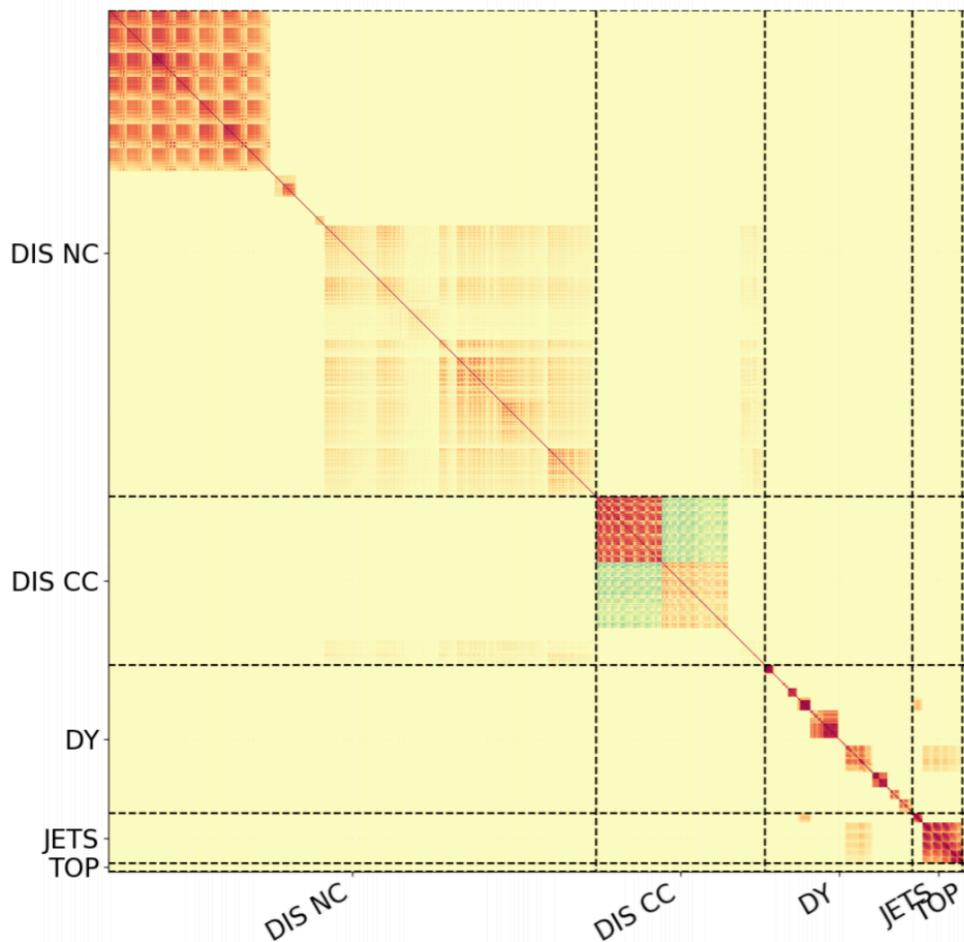
MISSING HIGHER ORDER UNCERTAINTIES

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

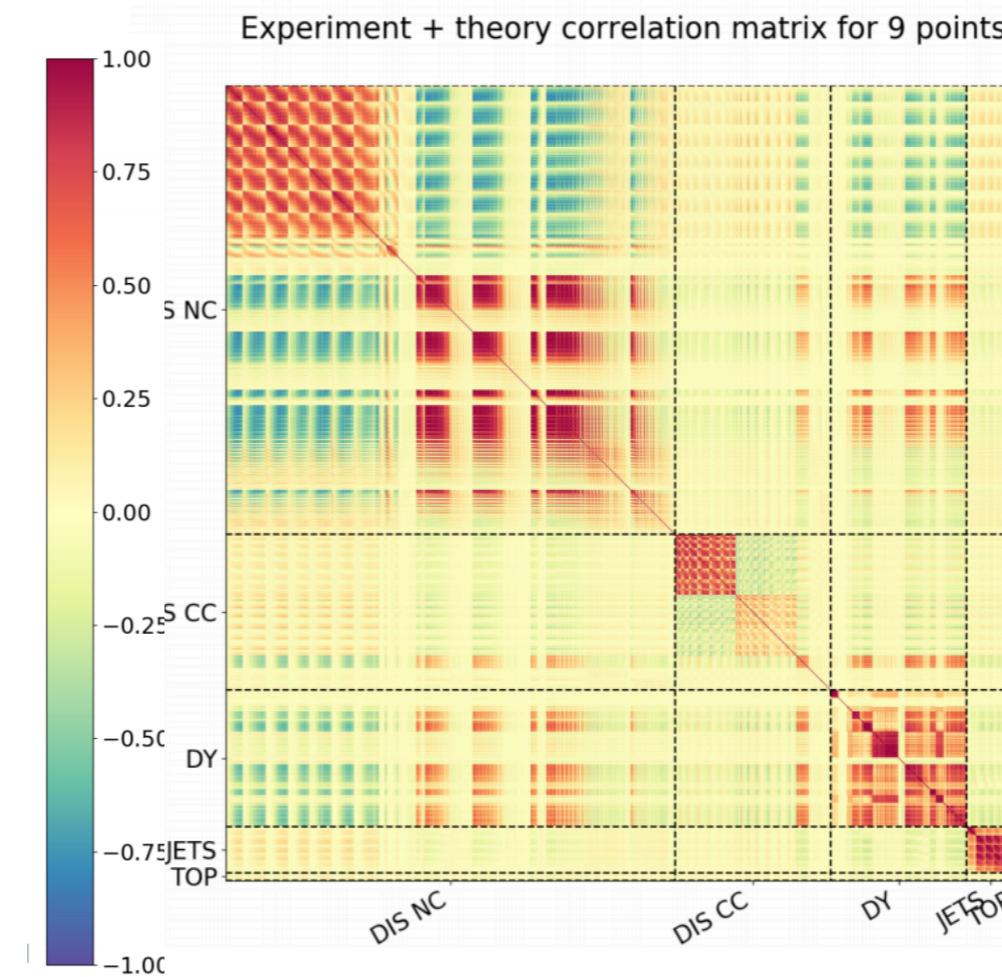
- ▶ Standard global PDF fits based on fixed-order NNLO QCD calculations
- ▶ **N3LO is now the precision frontier for theoretical predictions in PDF fits**
- ▶ **Global fits including MHOU reveal impact of missing higher orders in PDF fits**

$$\chi^2 = \sum_{m,n=1}^N (d_m - t_m)(\text{cov}_{\text{exp}} + \text{cov}_{\text{th}})^{-1}_{mn}(d_n - t_n)$$

Experiment correlation matrix



Experiment + theory correlation matrix for 9 points

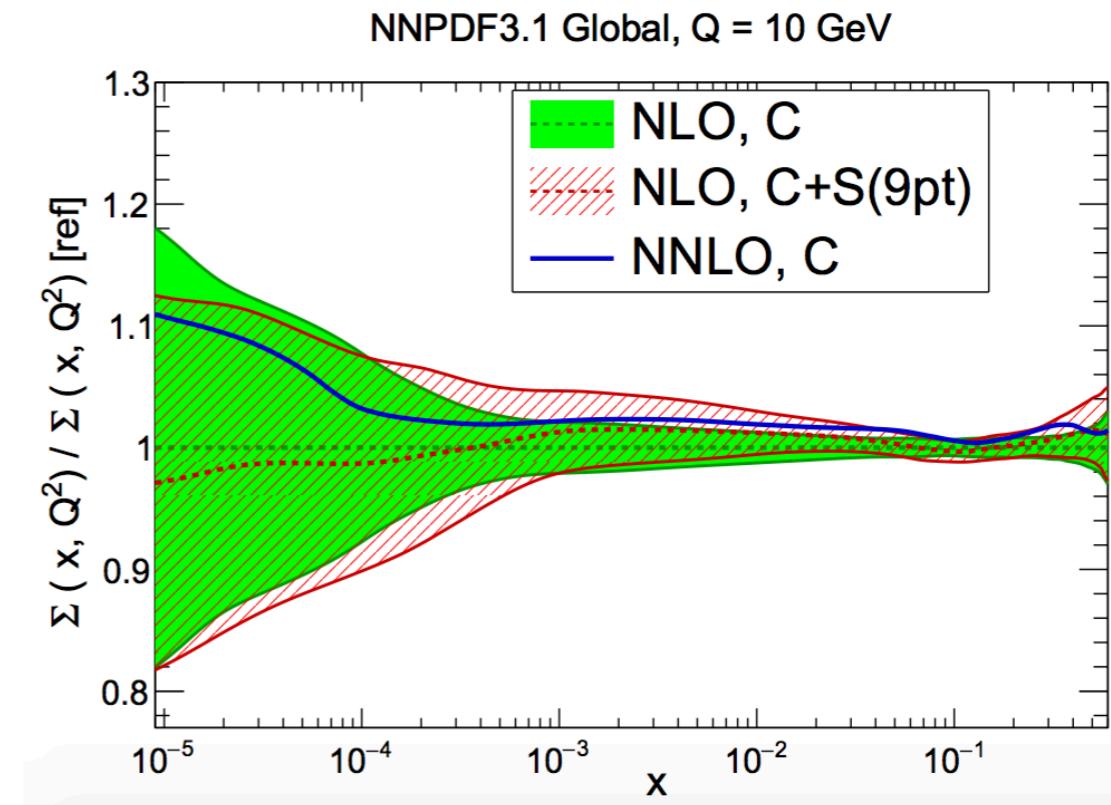
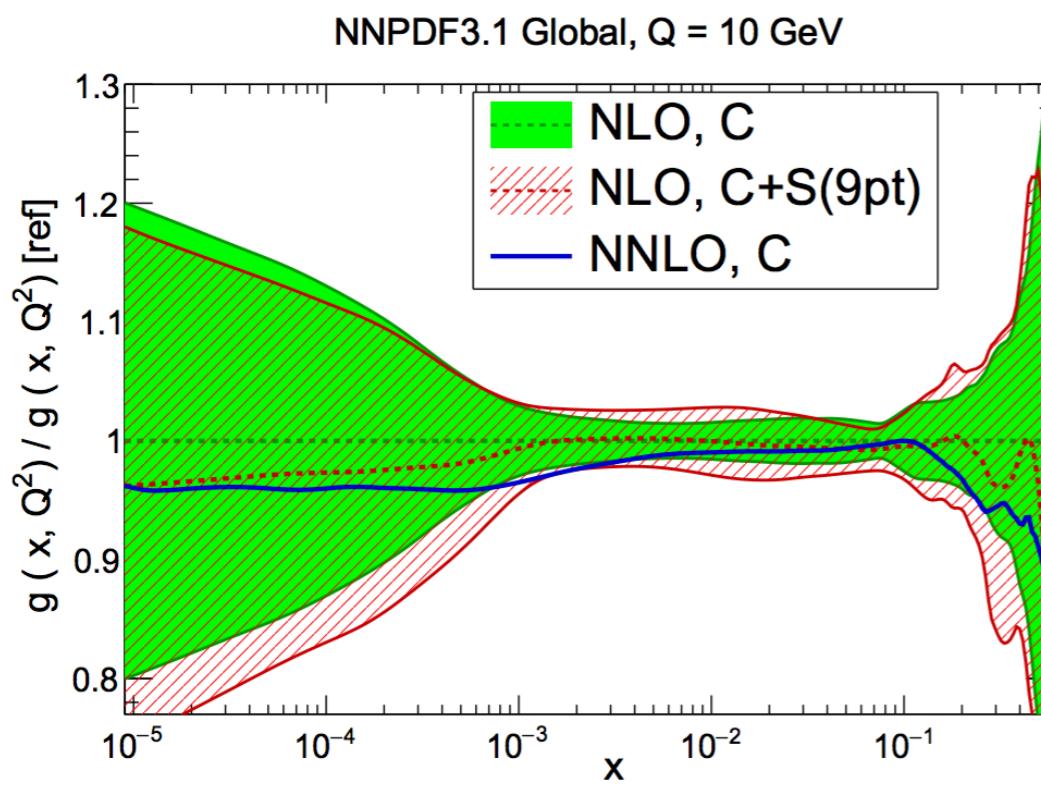


The idea:
Build a theory covariance matrix from scale-varied cross sections and combine it with the experimental covariance matrix

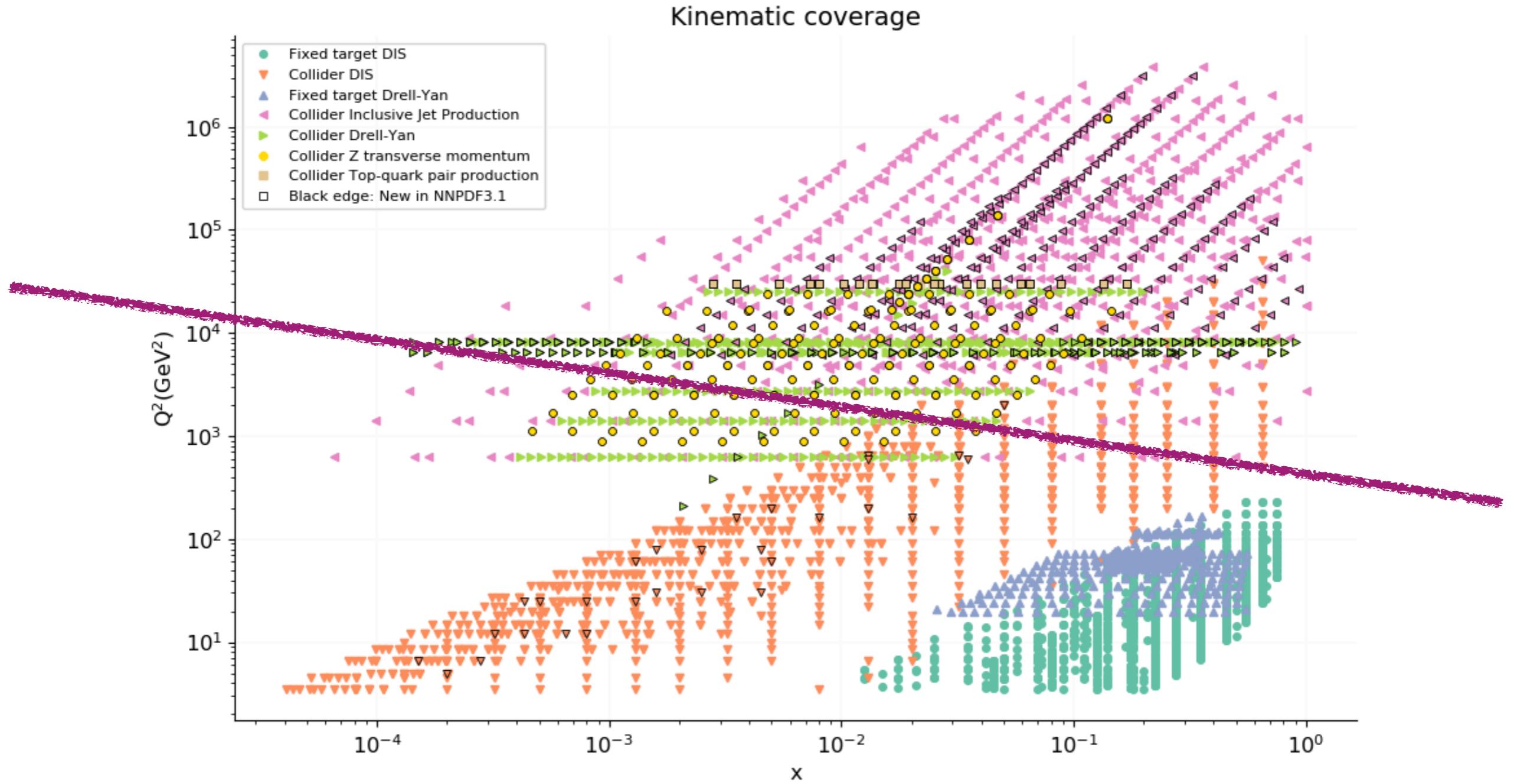
MISSING HIGHER ORDER UNCERTAINTIES

$$\sigma = \alpha_s^p \sigma_0 + \alpha_s^{p+1} \sigma_1 + \alpha_s^{p+2} \sigma_2 + \mathcal{O}(\alpha_s^{p+3})$$

- ▶ Standard global PDF fits based on fixed-order NNLO QCD calculations
- ▶ **N3LO is now the precision frontier for theoretical predictions in PDF fits**
- ▶ **Global fits including MHOU reveal impact of missing higher orders in PDF fits**
- ▶ **Results at NLO reveal mild increase in PDF uncertainties and NLO central values closer to NNLO central values**



BSM EFFECTS



- How to disentangle potential BSM effects?
- How to make sure that BSM effects are not fitted away by PDF parametrisation?

Carrazza, Degrande, Iranipour, Rojo, MU, Phys.Rev.Lett. 123 (2019) no.13, 132001
Greljo, Iranipour, Moore, Rojo, MU, Voisey in progress

Simultaneous determination of PDFs
and dim-6 SMEFT Wilson
coefficients in progress

CONCLUSIONS AND OUTLOOK

- Precision physics frontier at HL-LHC opens up new fascinating challenges also in the field of PDF determination
- Precise and accurate understanding of the proton structure is key to achieve accurate theoretical predictions
- HL-LHC projection: reduction of PDF uncertainties by factor 2-3, but to achieve this goal benchmark among PDF sets and thorough scrutiny of each PDF analysis is a must.
- Need: robust methodology (e.g. closure tests) and increased precision in theoretical predictions in PDF fits (N3LO, estimate of missing higher order uncertainties, EW corrections, photon and lepton PDFs)
- News: estimate of theoretical uncertainties associated with missing higher order and nuclear models in PDF fits, fit of the methodology, new tools to quantify the effects of new data.
- General aim towards global fits of all parameters that enter QCD analyses (PDFs + α_s , PDFs + EW parameters, PDFs + BSM EFT parametrisation...)
- Broad effort and cross-talk essential to advance and face these challenges